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Review of low-cost sensors for the ambient air monitoring of benzene and other volatile organic compounds

Spinelle L., Gerboles M., Kok G. and Sauerwald T.

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Review of low-cost sensors for the ambient air monitoring of benzene and other volatile organic compounds

ENV56 KEY-VOCs
Metrology for VOC indicators in air pollution and climate change

Literature and market review of low-cost sensors for the monitoring of benzene and other volatile organic compounds in ambient air for regulatory purposes

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Task 4.1: Review of the state of the art of sensor based air quality monitoring

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1 Description of Task 4.1, Review of the state of the art of sensor based air quality monitoring

1.1 Description of deliverable 4.1.1

The aim of this task is to perform a literature review of the state of the art of sensor based air quality monitoring in order to set the starting point of the following research and to avoid duplication of work. Inputs from the stakeholder committee, which includes the experts from EuNetAir Cost Action, will be sought.

Description of activities:

JRC and VSL, with input from experts of the stakeholder committee (D5.1.1), will jointly review commercially available sensors for monitoring VOCs and organic vapour compounds relevant to the Air Quality European Directive 2008/50/EEC (aromatics and in particular benzene). Combined with information provided by stakeholders, manufacturers and literature, the review will consider commercially available sensors, including:

- PID based sensors (JRC)
- semiconductor (resistive gas sensor) (JRC)
- portable on-line measuring devices (sensor arrays) (VSL)

The bibliographic collection will include the following topics: sensor description, the field of application in fixed, mobile, indoor and ambient air monitoring, range of concentration levels and limit of detection in air, model descriptions of the phenomena involved in the sensor detection process, gaseous interference, selectivity of sensors in complex VOC matrix, validation data in lab experiments and under field conditions. A report will be written which will provide input and recommendations for task 4.2. (JRC, VSL) (D4.1.1)

1.2 Time schedule and activities of deliverable 4.1.1

Deliverable number	Deliverable description	Participants (Lead in bold)	Delivery date
4.1.1	Report covering the collection of information about commercial available VOC, aromatic compounds and/or benzene sensors and portable on-line measuring devices for air pollution monitoring	**JRC**, VSL and UdS	June 2015

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2 Introduction

Volatile organic compounds (VOCs) are hazardous compounds that may cause damages to human for long time exposure. The principal compounds of interest consists of aromatics such as benzene, toluene, xylene, and ethylbenzene (BTEX) and aldehydes, such as formaldehyde, acetaldehyde.

In Europe, the monitoring of benzene in ambient air is mandatory according the European Directive 2008/50EC (AQD [1]) because of its health effect [2]. This Directive states that the reference method for the measurement of BTEX consists of active or on-line sampling followed by desorption and gas chromatography (EN 14662:2005 part 1, 2 and 3 [3]).This method is time consuming, expensive to implement and it needs skilled personnel to fulfil complex operations. While some implementation of this method may be transportable, it is not easily portable prohibiting estimation of the population exposure. Therefore, the reference method is not suitable to build dense networks of BTEX automatic monitoring sites to cover large areas or for the estimation of real-time human exposure assessment.

It is likely that future air quality assessment will rely on more spatial and exposure based monitoring of air pollutants [4] even though using measurement methods with lower data quality (the so-called indicative measurements in the AQD). The need for mobile applications and better spatial coverage can only be satisfied in reducing size and costs of monitoring devices using for example micro-sensors. Commercial low cost sensors represent a big opportunity for developing networks of VOC sensors able to monitor a large areas with a limited cost compared to reference measurements [2]. Moreover, the AQD allows using indicative measurements without restriction in the zones where the upper assessment threshold (UAT) is not exceeded while their implementation permit a reduction of 50 % of the minimum reference measurements where the UAT is exceeded. The Directive does not specify any indicative methods but it requires to show before use that the selected indicative method can meet a specific data quality objective (DQO). The DQO, defined as a relative expanded uncertainty of measurements, for indicative methods is less stringent than the one for reference measurements (30 % instead of 25%).

On the opposite of common indicative methods, e.g. diffusive samplers, micro-sensors are able to supply near to real time air pollution measurements by electronic means. This make possible assessing the effect of short term action plans [AQD, art. 24] and simplify reporting of air quality to the Internet [AQD, art. 26 and article 23 of the INSPIRE Directive [5]. Consequently, sensors would allow an easy integration of indicative measurements into AirBase, the database maintained by the European Environmental Agency (EEA) on behalf of the participating countries throughout Europe within the EIONET network. Currently, AirBase includes only a few measurements carried out using indicative methods.

Present technology of gas sensors has allowed the introduction on the market of various type of low cost sensors for air pollution monitoring: metal oxide sensors – (MOx), amperometric or potentiometric electrochemical cells, Photo Ionisation Detectors (PID), portable and micro GC (µGC)... However little or no performance evaluation study exists or does demonstrate that the DQO of the AQD can be reached. There have been only a few successful previous research studies with custom sensors and/or commercial sensors for quantitative determination [6,7] or identification of low level VOC [8]. Moreover, in general the information regarding the sensor metrological specifications and performances is spread and difficult to compare.

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[1] *DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2008 on ambient air quality and cleaner air for Europe, 11.6.2008 EN Official Journal of the European Union L 152/1*

[2] World Health Organization, 2010. Who guidelines for indoor air quality: selected pollutants. WHO, Copenhagen.

[3] *EN 14662:2005, 'Ambient air quality — Ambient air quality - Standard method for measurement of benzene concentrations - Part 1 : Pumped sampling followed by thermal desorption and gas chromatography; Part 2 : Pumped sampling followed by solvent desorption and gas chromatography; Part 3: Automated pumped sampling with in situ gas chromatography*

[4] *Batterman, S., Chambliss, S. & Isakov, V., 2014. Spatial resolution requirements for traffic-related air pollutant exposure evaluations. Atmospheric Environment, 94, pp.518–528.*

[5] *DIRECTIVE 2007/2/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 14 March 2007, establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)*

[6] *S. De Vito, E. Massera, M. Piga, L. Martinotto, G. Di Francia, On field calibration of an electronic nose for benzene estimation in an urban pollution monitoring scenario, Sensors and Actuators B: Chemical. 129 (2008) 750–757. doi:10.1016/j.snb.2007.09.060.*

[7] *L. Spinelle; M. Gerboles; M.-G. Villani; M. Aleixandre and F. Bonavitacola. Field calibration of a cluster of low-cost available sensors for air quality monitoring. Part. A: ozone and nitrogen dioxide, Sensors and Actuators, under review.*

[8] Leidinger, M., Sauerwald, T., Reimringer, W., Ventura, G., Schütze, A., 2014. Selective detection of hazardous VOCs for indoor air quality applications using a virtual gas sensor array. Journal of Sensors and Sensor Systems 3, 253–263. doi:10.5194/jsss-3-253-2014

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In 2005, Yamazoe [9] concluded that benzene levels in ambient air that were less than 100 nmol/mol were far out of being reached by commercially available gas sensors. In ten years the technological progress resulted in an improvement of sensor sensitivity and a few systems are able now to reach the nmol/mol or rarely sub-nmol/mol level of sensitivity for monitoring benzene in ambient air.

From another side, the AQD gives several requirements regarding metrological aspects setting very low levels of benzene to be monitored:

- the limit value (LV) for benzene is 5 µg/m³ (about 1.5 nmol/mol at 20 °C and 101.3 kPa) over a calendar mean calculated from individuals measurements. The latter measurement may last between 24 hrs and a few weeks for diffusive sampling, down to a few hours for active sampling and between one hr and a few minutes for on-line GC. Other important values defined in the AQD consist of the Upper Assessment and Lower Assessment Thresholds (UAT and LAT) which correspond to 3.5 and 2 µg/m³, respectively.
- the AQD states that the DQO shall be 30 % for indicative measurements. The DQO shall be assessed in the region of LV.

In this report, we decided to consider the use of sensors at traffic or background sites in urban and suburban area types. These micro-environments correspond to areas where benzene levels are expected to be highest within ambient air. It is important to characterize their air composition in order to establish the minimum necessary sensor sensitivity to benzene and the expected levels for compounds that may interference with sensor responses including their distribution, trends and correlation between each-other.

Additionally, the WHO Air Quality Guideline for Europe [10] establishes guidelines values for toluene, 260 µg/m³ over 1 week, for formaldehyde, 100 µg/m³ over 30 min and for tetrachloroethylene, 250 µg/m³ over 1 year. This document sets a guideline values for benzene corresponding to the concentrations levels associated with an excess lifetime risk of 1/10 000, 1/100 000 and 1/1 000 000 equal to 17, 1.7 and 0.17 µg/m³, respectively. In 2010, the WHO Guidelines for Air Quality in Indoor Air [11] included, among others, guideline values for benzene, formaldehyde, naphthalene, polycyclic aromatic hydrocarbons especially benzo[a]pyrene. The Guidelines-2010 confirmed the guideline values given in 2000[10] for benzene.

The Work Package 4 (WP4) of the EURAMET Key-VOC project aims at testing VOCs sensors for AQD regulatory purposes with laboratory and in-situ assessments. As part of this project, a literature search has been conducted to survey available technologies and identify the most promising methods. The original goal was to compute a list of cheap sensors, hoping to find items within an initial price limit of 1000 €. This limit had to be increased up to 5000 € because of the lack of commercial instrument within 1000 €. The report provides a summary of the advantages and disadvantages of each sensor technology identified from our literature review. Our main interest is on sensors for benzene measurements. However, where easily reported information on BTEX and other aromatics or VOCs is also given.

Hereafter, the outline of the report is given:

1. the different principles of operations of sensors,
2. review of commercial gas sensors for benzene and their specifications for over 50 commercial sensors taking into account the specifications of the AQD for benzene monitoring,
3. review of the literature for the most relevant research projects aiming at improving the monitoring of benzene, BTX or other VOCs with these sensor systems,
4. we give a list of sensors that seems to be most appropriate for carrying out the laboratory and field experiments in the rest of the Key-VOCs WP4 program of tests.

This information is given for the convenience of users of this document and does not constitute an endorsement by the authors nor the institutions to which they are affiliated of any of these products.

3 Principle of operation and type of sensors

In this report, specific sensor technologies are categorized into several broad groups, and these groups are then evaluated for use in subsurface, long-term applications. Nearly the totality of VOC small commercial sensors is based on five different technologies that are presented in the following sub sections:

- Photo Ionization Detectors (PID), both portable hand held instrument and OEMs,
- OEM Metal oxide sensors (MOx) with change of conductivity instead of chemical reaction,

[9] Yamazoe, N., 2005. Toward innovations of gas sensor technology. Sensors and Actuators B: Chemical 108, 2–14. doi:10.1016/j.snb.2004.12.075

[10] WHO. Air quality guidelines for Europe; second edition. WHO Regional Publications, European Series, No. 91, 2000.

[11] *World Health Organization, Who guidelines for indoor air quality: selected pollutants, WHO, Copenhagen, 2010.*

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- OEM Electrochemical sensors either of amperometric or potentiometric type,
- Optical sensors including UV portable spectrometers,
- and portable or micro - gas chromatograph (µGC) that combines micro column with MOx or PID OEM as detectors. Flame ionization detector (FID) are generally not considered in this review because of the need of an external hydrogen source for operation. Bench top instruments are excluded in this category for the lack of handiness and their price.

Original equipment manufacturer (OEM) is a term used when one company makes a part or subsystem that is used in another company's end product. The term is used in several ways, each of which is clear within a context. The term sometimes refers to a part or subassembly maker, sometimes to a final assembly maker, and sometimes to a mental category comprising those two in contrast to all other third party makers of parts or subassemblies from the aftermarket.

In order to characterize sensor performance a set of parameters is used. Where available, the most important parameters [12] listed below, are used in the following sensor market review. For this literature review, the focus will be put on the sensitivity, limit of detection and dynamic range only. The sensor metrological parameters consist of:

- Sensitivity is a change of measured signal per analyte concentration unit, i.e., the slope of a calibration graph. This parameter is sometimes confused with the detection limit.
- Selectivity refers to characteristics that determine whether a sensor can respond selectively to a group of analytes or even specifically to a single analyte.
- Stability is the ability of a sensor to provide reproducible results for a certain period of time. This includes retaining the sensitivity, selectivity, response and recovery time.
- Limit of detection is the lowest concentration of the analyte different from naught that can be detected by the sensor under given stable conditions, particularly at a given temperature, humidity, air matrix... Generally, the detection is computed as 3 times the standard deviation of the responses of sensor measuring an air mixtures without the analyte of interest,
- Resolution is the lowest concentration difference that can be distinguished by sensor. Often the resolution and limit of detection as confused in the datasheet of sensors
- Dynamic range is the analyte concentration range between the detection limit and the highest limiting concentration.
- Linearity is the relative deviation of an experimentally determined calibration graph from an ideal straight line.
- Response time is the time required for the sensor to respond to a step concentration change from zero to a certain concentration value. Generally, the response time is given as t90, the time needed by the sensor to reach 90 % of its final value.
- Recovery time is the time it takes for the sensor signal to return to its initial value after a step concentration change from a certain value to zero.
- Hysteresis is the maximum difference in output when the value is approached with an increasing and a decreasing analyte concentration range.
- Life cycle is the period of time over which the sensor will continuously operate.

For metal oxide sensors, additional parameters may be given:

- Working temperature is usually the temperature that corresponds to maximum sensitivity of MOx sensors.

3.1 Existing reviews of sensors

Only a few literature reviews exist about low-cost sensors for VOC in the nmol/mol range for monitoring air quality in ambient air. In 2001, Ho et al [13] presented a review of sensors that were capable of detecting and monitoring VOC for long-term air pollution monitoring. The review included chromatographic/spectrometric

[12] *V. E. Bochenkov, G. B. SergeeV, Metal oxide nanostructure and their applications, ISBN: 1-58883-176-0 , Copyright © 2010 , American Scientific ublishers*

[13] *Clifford K. Ho, Michael T. Itamura, Michael Kelley, and Robert C. Hughes, Review of Chemical Sensors for In-Situ Monitoring of Volatile Contaminants, SANDIA REPORT, SAND2001-0643, Unlimited Release, Printed March 2001, http://www.sandia.gov/sensor/SAND2001-0643.pdf*

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sensors; conductimetric MOx sensors, amperometric/potentiometric sensors; acoustic wave sensors; and optical sensors. The authors found that only portable gas chromatographs, ion mobility spectrometers (IMS) and portable mass spectrometers could reach a limit of detection in the nmol/mol range. These included:

- Environmental Vapor Monitor (EVM II), a Gas Chromatograph/Ion Mobility Spectrometer (IMS) [14],
- Hapsite, a Gas Chromatograph/Mass Spectrometer [15],
- another GC/IMS instrument from DLK spectro that seems not to be supplied any more [16].

However these instruments are too expensive for our objective since we look for low-cost sensors. The author concluded that the most viable sensors for in-situ chemical sensing were likely polymer absorption chemiresistor, MOx sensors, fiber-optic sensors, and surface-acoustic-wave sensors. This conclusion was drawn in absence of sensitivity, selectivity and any type of evaluation study. It was based on the simplicity and robustness of these types of sensors.

More recently, Allouch e al. [17] reviewed recent research studies for optical and colorimetric-based portable devices for real time BTEX analysis. Within all instruments included in this review, only two systems were suitable for the low nmol/mol range. The 1st system used a micro-fluidic UV portable spectrometer with a silicate absorbent and later thermal desorption which resulted in a limit of detection of about 10 nmol/mol for hourly values [18]. The system was further improved to reach a limit of detection of about 1 nmol/mol for 30 min averages while resulting in a more complicated setup including a pulse pump system and new detection cell [19]. The 2nd prototype [20] was based on the variation of the reflected light intensity when BTEX gases are present in a detection tube which contains an optical fiber coated with a polymeric sensitive film. The change in the intensity was proportional to the amount of BTEX present inside the tube. The sensor design was composed of a concentration system (12 cm length) and a detection cell (7.2 cm length). Gaseous BTEX were transmitted to the glass tubing that contains a PDMS (polydimethysiloxane) layer for the adsorption and desorption processes and finally to the detection tube that contained the coated optical fiber. A thin film of polysiloxane, deposited by uniform spray coating technology, had been used for this sensitive film. The most convincing results have been obtained at a diode wavelength of 650 nm and a sampling time of 25 min at 200 ml/min. They have been checked using a gas chromatography-flame ionization detector (GC-FID). The detection limit was found to be around 2.5 nmol/mol for benzene without the need for a pre-concentration step. Despite the fast, real-time and on-site monitoring of BTEX provided by this sensor, it is still chemicals consuming. In addition, polymer-based sensing is limited in terms of durability.

Marc et al [21] described the state of the art for micro chromatographic systems (µGC) of the lab-on-a-chip type (LOC) and for portable analyzers for the detection and identification of specific compounds or groups of compounds present in ambient air (indoor or outdoor). In this review, the authors cite the lab-on-a-chip sensor developed by Hallidays et al. [22]. This preliminary development consists of a planar 2-dimensional GC chip micro-fabricated system using a PID detector suitable for the separation of VOCs and compatible for use as a portable measurement device. This low-power device showed good separation performance for a small set of VOCs and promising preliminary results for the separation of µmol/mol gas mixtures of a set of VOCs.

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14 http://www.femtoscan.com/evm.htm
15 http://www.inficonemergencyresponse.com/
16 http://www.spectro.com/pages/e/index.htm
17 Allouch, A., Le Calvé, S., Serra, C.A., 2013. Portable, miniature, fast and high sensitive real-time analyzers: BTEX detection. Sensors and Actuators B: Chemical 182, 446–452. doi:10.1016/j.snb.2013.03.010
18 Horiuchi, T. et al., 2006. Portable Aromatic VOC Gas Sensor for Onsite Continuous Air Monitoring with 10-ppb Benzene Detection Capability. NTT Technical Review, 1, p.30–.37
19 *S. Camou, T. Horiuchi, and T. Haga, "Ppb Level Benzene Gas Detection by Portable BTX Sensor Based on Integrated Hollow Fiber Detection Cell," Proc. of IEEE Sensors 2006, Daegu, Korea, 2006.Camou, S., Tamechika, E. & Horiuchi, T., 2012. Portable Sensor for Determining Benzene Concentration from Airborne/ liquid Samples with High Accuracy. NTT Technical Review, 10(2), pp.1–7.*
20 *Silva, L.I.B. et al., 2009. Polymeric nanofilm-coated optical fibre sensor for speciation of aromatic compounds. International Journal of Environmental Analytical Chemistry, 89(3), pp.183–197.*
21 Marć, M. et al., 2015. Current air quality analytics and monitoring: A review. Analytica chimica acta, 853, pp.116–126.
22 *Jaydene Halliday, Alastair C. Lewis, Jacqueline F. Hamilton, Christopher Rhodes, Keith D. Bartle, Phillip Homewood, Robin J.P. Grenfell, Brian Goody, Alice Harling, Paul Brewer, Gergely Vargha, Martin J.T. Milton, Lab-on-a-Chip GC for Environmental Research, LCGC Europe, Volume 23, Issue 10, pp. 514-523, Nov 1, 2010, http://academy.chromatographyonline.com/lcgc/article/articleDetail.jsp?id=696156&sk=&date=&pageID=7*

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A more sensitive VOC analyser was also highlighted consisting of the Palm Portable Mass Spectrometer (PPMS) [23].The PPMS was shown to be able of real-time monitoring of trace levels of benzene, toluene, and ethylbenzene in air. The system consisted of an atmospheric pressure chemical ionization for direct analysis of gas-phase samples on a miniature mass spectrometer. A limit of detection of 0.2, 0.5 and 0.7 µmol/mol were achieved for benzene, toluene and xylene, respectively, for air samples without any sample pre-concentration. The linear dynamic ranges of benzene, toluene, and ethylbenzene are limited to approximately two orders of magnitude by saturation of the detection electronics.

Table 1: Sensitivity of sensors for the measurement of benzene or other VOc

Reference	Target gas	Principle	Limit of detection	Response time, min	Sensitivity factor, (µmol/mol.min)	Year
Horiuchi et al. [18]	Benzene	Absorption/desorption/UV detec.	10 nmol/mol	60	0.600	2006
Camou *et al* .[19]	Benzene, toluene, xylene	Absorption/desorption/UV detec.	1 and 0.3 nmol/mol	30	0.030	2006, 2012
Silva *et al.*[20]	Benzene	Reflexion light	2.5 nmol/mol	30	0.075	2009
Halidays *et al.*[22]	VOC	Lab-on a chip GC	2 µmol/mol	30	60	2010
Huang *et al.*[23]	VOC	Portable MS	0.2 nmol/mol	5 s	0.000017	2010

3.2 Photo Ionization Detector

3.2.1 Principle

Photo-Ionization Detector (PID) instruments are ion detectors which uses high-energy photons, typically in the ultraviolet (UV) range. UV light excites the molecules, resulting in temporary loss of electrons in the molecules and the formation of positively charged ions. The gas becomes electrically charged and the ions produce an electric current, which is the signal output of the detector. The higher the concentration of the component, the more ions are produced, and the higher the current. The ions recombine after passing the detector to reform their original molecules. PID are broad band detectors and not selective at all as they ionize everything with an ionization energy less than or equal to the lamp output. A Photo Ionization Detectors (PID) is shown in Figure 1.

The test gas (1) diffused through a membrane filter at the top of the photo-ionization cell and freely diffuses into and out of the underlying chamber formed by the filter, housing walls, and a UV lamp window. The lamp emits photons (shown by arrows) of high energy UV light, transmitted through the window. Photo-ionization occurs in the chamber when a photon is adsorbed by the molecule, generating two electrically charged ions, one positively charged, X+, and one negatively charged, Y-. An electric field, generated between the cathode and anode electrodes, attracts the ions. The resulting current is proportional to the concentration of the VOC, is measured and used to determine the gas concentration.

[23] Huang, G., Gao, L., Duncan, J., Harper, J.D., Sanders, N.L., Ouyang, Z., Cooks, R.G., 2010. Direct detection of benzene, toluene, and ethylbenzene at trace levels in ambient air by atmospheric pressure chemical ionization using a handheld mass spectrometer. Journal of the American Society for Mass Spectrometry 21, 132–135. doi:10.1016/j.jasms.2009.09.018

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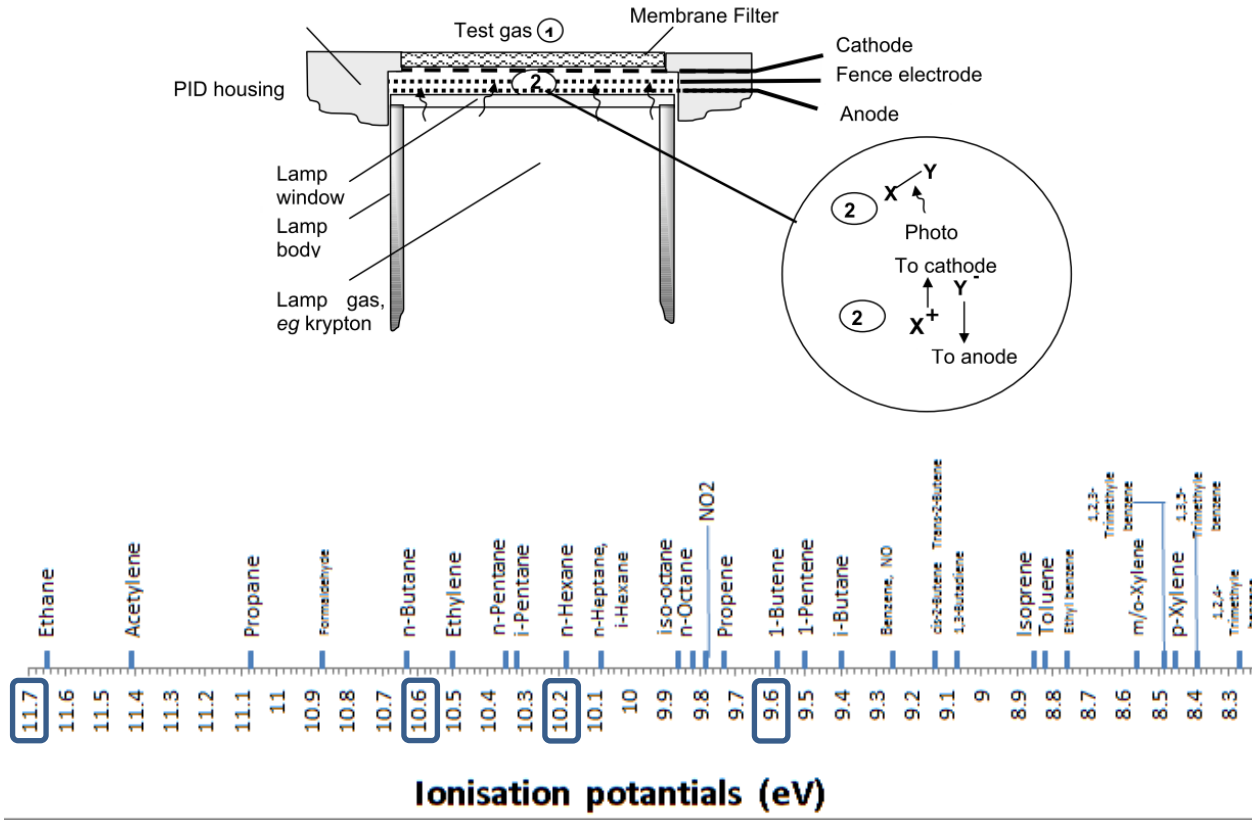

Figure 2: Photoionization energy of common VOC in the range of the Argon lamp (E < 11.7 eV)

Most VOCs can be detected by PID. Notable exceptions are low molecular weight hydrocarbons. Each VOC has a characteristic threshold energy of light (photon energy) which, when directed at the VOC, causes it to fragment into ions. This is called the Ionization Potential, or IP. VOCs are ionized (and hence detected) if light of photon energy greater than the IP interacts with the gas sample. The peak of photon energy generated in a detector depends on the PID lamp used: Xenon = 9.6 eV, Deuterium = 10.2 eV, Krypton = 10.6 eV and Argon = 11.7 eV. Hence, the use of an argon lamp leads to detection of the largest range of volatile compounds, while using a Xenon lamp can increase selectivity. A greater instability is generally observed for 11.7eV lamp which are not recommended. Spectral fingerprint do not typically vary with the type of lamps, so relative responses to a particular gas, e.g. benzene, to a particular lamp, e.g. krypton, does not vary from lamp to lamp. However, the intensity of lamps does vary to some extent, leading to a difference in absolute response to the calibration gas. The higher the lamp energy is, the more sensitive is the sensor while selectivity decrease as a broader range of compounds can be photo-ionized. The most common lamp is the Krypton one (10.6 eV) with a suitable equilibria between sensitivity and selectivity. For BTEX a Xenon lamp (9.6 eV) improves selectivity although leading to less sensitive measurements (see the ionization potentials of common VOC in Figure 2). The usual size of sensors is around 20 mm x 17 mm, with a weight of 8 g and a power consumption of 110 mW.

PID are affected by linearity deviations but manufacturers generally give this information for the µmol/mol range of concentrations. Above 10 µmol/mol the linearity of the sensor decreases but also does the noise. The response is in general very quick, down to a few seconds even if the total response time is limited by the diffusion of molecules towards the detector in field application.

There is generally a small temperature dependence and the humidity sensitivity is below an equivalent response of 0.2 µmol/mol for changes of 90% relative humidity. Although PIDs are very stable they require frequent calibration. The manufacturer generally recommends a recalibration once a month in clean environments with low particle count and low VOCs present.

Generally, linear model are well suited for calibrating PID sensors within their linear ranges. But since the lamps can vary one from each other, each lamp replacement requires a new calibration. The best way to

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calibrate PIDs to different compounds is to use a standard of the gas of interest. However, correction factors have been determined that enable the user to quantify a large number of chemicals using only a single calibration gas, typically isobutylene. Correction factors can be used after calibration to read in isobutylene-equivalents by multiplying the reading by the correction factor (CF) to obtain the concentration of the gas being measured. The correction factor is defined as the response of isobutylene (IBE)-calibrated PID to an equal concentration (µmol/mol) of the compound of interest. Thus, the higher the correction factor, the lower the sensitivity to the compound of interest. In fact for BTEX, the CFs being around 0.5 (See Appendix I: PID correction factors for various gases and lamp energies (9.6, 10.6 and 11.6 eV) calibrated to isobutylene on PID corrections factors) for all lamp energies, PID are about two times more sensitive for BTEX than to IBE. The best limit of detection of PID are about 0.25 nmol/mol (see paragraph below and Appendix III: Review of sensor specifications and data sheets on market evaluation of sensors).

To account for any drift during the measurements, one can make isobutylene measurements before and after the sample measurements and take the average response to the isobutylene standard. Using the CFs, it becomes possible to estimate the sensitivity and limit of detection of different PIDs for the gas compounds of interest.

3.2.2 Commercially available sensors

The main PID sensors of OEMs consists of the Ion Science (UK) model ppb MiniPiD white, AlphaSense (UK) model PID-AH for VOCs, Mocon-Baseline (USA) models piD-TECH eVx Blue 045-014 and piD-TECH plus, 043-235. These small sensors can reach a low limit of detection due to their high sensitivity for benzene up to sub-nmol/mol for the MiniPiD white, PID-AH and piD-TECH eVx Blue, respectively (see Table 2 and Figure 3). Unfortunately, none of these sensors are selective to a particular VOC, and even with a xenon lamp of 9.6 eV benzene, toluene and xylene cannot be distinguished as the Ionisation Potential of these compounds is lower than the energy of the lamp.

A few manufacturers propose portable instrument displaying real time measurements (Dräger model Multi-PID 2, Baseline-Mocon model VOC-Traq, GrayWolf Inc models AdvancedSense-DirectSens, Ion Science Ltd model Club Personal and Tiger Select, RAE Systems Inc. model UltraRAE 3000 and model ppbRAE 3000, PID Analysers model 102+). Some of them also include a selective absorbing cartridge for benzene (Drager model Multi-PID 2, Ion Science model Tiger Select and RAE Systems Inc. model UltraRAE 3000). Unfortunately, the sensitivity of the portable instruments is lower than the OEM sensors especially for the ones selective to benzene. This is likely because of the added absorbing cartridge. The best resulting limit of detection was found to be 50 nmol/mol for the Dräger and RAE instruments and 10 nmol/mol for the Ion Science Tiger Select benzene (see Figure 3). Generally, the price of OEM PID lays around 500 € while the price of portable hand help PID sensors is about 5000 €.

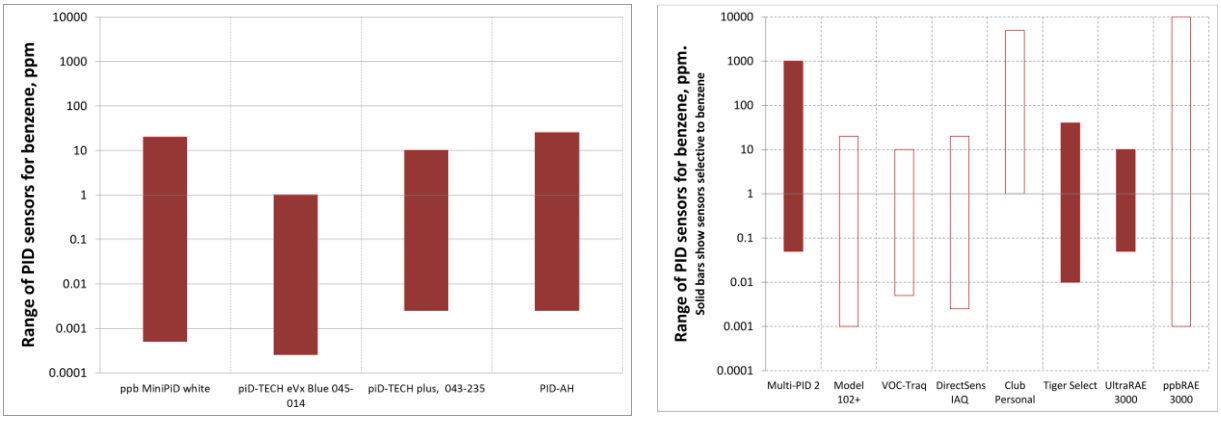

Figure 3: Dynamic range of PID sensors of OEM (left) and portable PID sensors (right) with 10.6 eV lamps

Note that the dynamic range shown is based on the manufacturers' specification, and is not estimated in a uniform way by different manufacturers. Also remark that a sensor may be very useful outside its specified range by using a non-linear calibration function.

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Table 2: Sensitivity, response time and limit of detection of the commercially available PID sensors

Model	Manufacturer	Limit of detection for benzene, µmol/mol	Sensitivity for IBE V/µmol/mol	Selectivity	Stability (drift)	range for IBE, µmol/mol	Resp. time, s
ppb MiniPiD white	Ion Science	0.0005	0.025	All compounds with IP lower than the energy of the lamp are detected. Effect from humidity and temperature	Frequent calibration, periodicity lower than a month	0.001- 40	2
piD-TECH eVx Blue 045-014	Baseline-Mocon	0.00025	1.125			0.0005-2	a few seconds
piD-TECH plus, 043-235	Baseline-Mocon	0.0025	0.125			0-20	<5
PID-AH for VOCs	Alphasense LTD	0.0005	>0.020			0.0005-50	<3
Multi-PID 2	Dräger	0.050	Not relevant	benzene pre-filter	No data	0.100-2000	3
Model 102+	PID Analysers	0.001	Not relevant	All VOCs with IP < 9.6, 10.2 or 11.7 eV	No data	0.001-20	1
VOC-Traq	Baseline-Mocon	0.005	Not relevant	All VOCs with IP < 10.6 eV	No data (once a month?)	0.010-20	10
Club	Ion Science	0.0005	Not relevant	All VOCs with IP < 10.0 eV	No data (once a month?)	0.001-5000	13
Tiger Select benzene	Ion Science	0.010 (resolution 0.001)	Not relevant	benzene pre-filter	No data (once a month?)	0.001-5000	< 2
AdvancedSense DirectSens IAQ	Graywolf	0.0025	Not relevant	All VOCs with IP < 10.6 eV	No data (once a month?)	0.005-20	<60
UltraRAE 3000	RAE Systems	0.050	Not relevant	9.8 eV lamp and benzene absorbing tube	No data (once a month?)	0.050-200 (benzene)	60
ppbRAE 3000	RAE Systems	0.0005	Not relevant	All VOCs with IP < 10.6 eV	No data (once a month?)	0.001-10	2

IBE: Iso-butyl ethylene, the ratios of IBE to benzene are 0.55 for an 9.8-eV lamp, 0.5 for an 10.6-eV lamp and 0.6 for an 11.6-eV lamp, IP: ionization potantiel

3.2.3 Literature survey

Peng et al., [24] proposed an improvement of signal generation system of PID sensor. Compared with commercial instruments the sample was directed to flow across the lamp window, rather than toward the lamp. Moreover a new and simple automatic self-cleaning technique, which effectively eliminates contaminants and substantially reduces drift, had also been adopted. The use of new electrodes had effectively reduced the background noise and dead volume of the PID. As a result of this new design the PID should be more compatible with rapid portable GC in environmental monitoring, because of elimination of most of the tedious cleaning and calibration previously necessary.

3.3 Electrochemical sensors

3.3.1 Principle of amperometric sensors

Electrochemical gas sensors are among the oldest known technology and widely used for concentration measurements. There are different basic principles for electrochemical sensors: potentiometric sensors if a

[24] Peng, F.M., Xie, P.H., Shi, Y.G., Wang, J.D., Liu, W.Q., Li, H.Y., 2007. Photoionization Detector for Portable Rapid GC. Chromatographia 65, 331–336. doi:10.1365/s10337-006-0169-3

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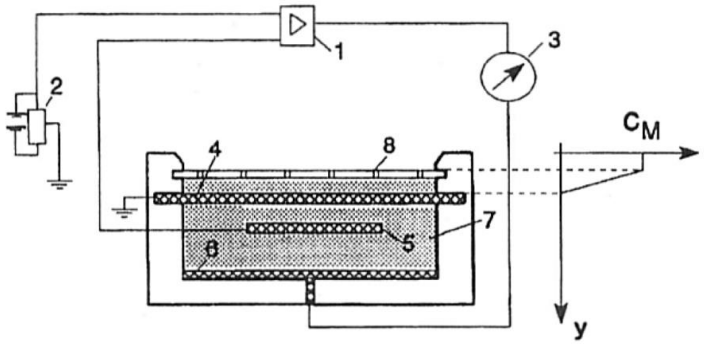
difference of potentials is measured or amperometric if the current of an oxido-reduction reaction is measured. Electrochemical reactions are always based on the transfer of a charge from an electrode to another phase (electrolyte), which can be solid [25], gel-like (or organic gel as in the case of City Technology), liquid or gaseous electrolytes (e. g. for SGX Sensortech). This process is based on a chemical reaction of the electrode as well as transport of charges through the electrolyte. To build an electrochemical cell at least two electrodes are required. Nowadays, the majority of amperometric sensors for measurement at low levels include 3 electrodes (measuring/working, counter and reference electrodes). Some manufacturer also add a fourth electrodes for monitoring physical changes and drift in the sensor architecture (e. g. for AlphaSense and Membrapor).

Figure 4 shows the schematic of an amperometric sensor, which is composed of the required measuring and counter electrodes and an additional reference electrode. The gas to be measured diffuses into the sensor and to the measuring electrode where a direct electron transfer or a chemical reaction leading to an electrochemical process is taking place. These reactions produce an internal current which is measured outside giving an electric current proportional to the gas concentrations [26] following the Nernst Law for electrochemical reactions [27].



Schematic of an amperometric sensor:
- 1 potentiostat,
- 2 reference voltage adjustment,
- 3 ampere meter,
- 4 measuring electrode,
- 5 reference electrode,
- 6 counter electrode,
- 7 electrolyte,
- 8 diffusion barrier [28]

Figure 4: schematic of an amperometric sensor

These are low cost, low power, compact sensors. As for PIDs, electrochemical cells are broad band sensors, but with a different profile: PIDs will measure more VOCs than electrochemical cells, and with much greater sensitivity. If one wishes to measure a VOC with electrochemical cells, then it is necessary to optimise the electrochemical sensor for the target VOC: each VOC will require a different ideal bias voltage between the reference and the measuring electrode in order to reach the best sensitivity. This is not an easy task. Electrochemical cells respond in about 180 seconds depending on the air temperature.

Amperometric sensors show little selectivity and a sensitivity down to the high nmol/mol range. This type of sensors can be tailored to a specific target gas in many ways. First of all a specific chemical reaction in upstream of the electrochemical reaction can be used to control the selectivity. Some characteristics of the diffusion barrier like porosity or pore distribution can for example be adjusted to the target gas. Also the bias voltage, the type of electrolyte, the material and structuring of the measuring electrode etc. which all contribute to the selectivity of an amperometric gas sensor.

The usual size of these sensors is about 20 millimeters and the electrical consumption is very low owing to the low electrical current signal generated. The main power requirement is the amplification of the very low level signal required to read the measurement. The electrodes composition gives selectivity and sensitivity to diffuse

[25] *Kumar, R.V.; Iwahara, H. Solid electrolytes, In: K.A. Gschneidner, Jr. and L. Eyring, Editor(s), Handbook on the Physics and Chemistry of Rare Earths, Elsevier, 2000, Volume 28, Pages 131-185, ISSN 0168-1273, ISBN 0444503463, 10.1016/S0168-1273(00)28006-9*

[26] *P. Jacquinot, A.W.E. Hodgson, P.C. Hauser, B. Müller, B. Wehrli, Amperometric detection of gaseous ethanol and acetaldehyde at low concentrations on an Au–Nafion electrode, Analyst. 124 (1999) 871–876. doi:10.1039/A809685F.*

[27] *Kumar, R.V.; Fray, D.J. "Development of solid-state hydrogen sensors", Sensors and Actuators, Volume 15, Issue 2, 1988, Pages 185-191*

[28] *Wiegleb, G. (ed.): Industrielle Gassensorik: Messverfahren – Signalverarbeitung – Anwendungstechnik – Prüfkriterien, expert-Verlag, RenningenMalmsheim, 2001*

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target gases such as VOCs [29], NH_3 [30], O_3 [31], NO_2 [32] and NO [33,34]). The electrodes can be composed of different materials and different supports, for example SGX Sensortech uses porous PTFE with catalytic materials. The traditional electrolytic sensors have a very high range of detection of gases [35] but new sensors can achieve low detection limits [36]. The usual measuring range for VOCs is between 100 nmol/mol – 20 µmol/mol. The error tends to be similar in all the sensors from all the manufacturers and the sensors show a deviation from linearity of about 2-5%, but in some cases the error can rise up to 10%. By selecting different electrode materials the reaction rate to several gases can be fine-tuned, but not completely eliminated.

Some electrolytic sensor need humidity to function correctly and a very low humidity can lead to problems. Others sensors based on solid materials are not so dependent on ambient humidity. The temperature has also an influence on the sensor response, but it can be modeled. Some studies have shown dependence on wind velocity in ambient applications probably influencing the chemical equilibrium on the surface [37] or the diffusion through the membrane of these sensors. The sensors show long term stability, for Nemoto and SGX Sensortech with drift values between 2% and 15% per year. Some problems of stability can arise from the lack of oxygen in the sensor. While the consumption of oxygen is very low and the sensor can operate long times without being exposed to oxygen, a constant exposure to oxygen should be supplied.

The calibration of these sensors follows the Nerst law and are well calibrated for the gases to measure and are either linear or logarithmic [29]. The evaluation of uncertainty for amperometric sensors is described in Helm et al. [38].

3.3.2 Commercially available sensors

We could not find any commercial manufacturer of potentiometric sensors for VOCs measurement, while there a few well-known manufacturer of amperometric sensors for VOCs. They generally propose 3-electrode amperometric sensor type adjusted to measure ethylene oxide with a number of inorganic and organic interfering compounds (see Appendix III: Review of sensor specifications and data sheets):

- City Technology (UK) model 3ETO CiTiceL and 4ETO CiTiceL, 7ETO CiTiceL,
- Alphasense LTD (UK) model ETO-A1, ETO-B1,
- Membrapor AG (CH) model ETO/M-10 and ETO/C-20,
- and SGX Sensortech (CH) model EC4-10-ETO.

The limit of detection of all these sensors (for ethylene oxide) is too high for air quality monitoring with the best figure reaching 50 nmol/mol (see Figure 5and Table 3). All sensors exhibit similar sensitivity between 1.9 and 2.8 µA/µmol/mol leading to low signal when measuring VOC in nmol/mol or sub nmol/mol range that cannot be distinguished from the electronic noise of the sensors or the measuring data acquisition systems even

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29 Mori, M., Sadaoka, Y., 2010. Potentiometric VOC detection at sub-ppm levels based on YSZ electrolyte and platinum electrode covered with gold. Sensors and Actuators B: Chemical 146, 46–52. doi:10.1016/j.snb.2010.02.001

30 Nagai, T.; Tamura, S.; Imanaka N. «Solid electrolyte type ammonia gas sensor based on trivalent aluminum ion conducting solids», Sensors and Actuators B: Chemical 147, no. 2 (2010): 735-740

31 R. Knake, P.C. Hauser, Sensitive electrochemical detection of ozone, Analytica Chimica Acta. 459 (2002) 199–207. doi:10.1016/S0003-2670(02)00121-6.

32 M. Ono, K. Shimanoe, N. Miura, N. Yamazoe, Reaction analysis on sensing electrode of amperometric NO2 sensor based on sodium ion conductor by using chronopotentiometry, Sensors and Actuators B: Chemical. 77 (2001) 78–83. doi:10.1016/S0925-4005(01)00676-1.

33 M. Ono, K. Shimanoe, N. Miura, N. Yamazoe, Amperometric sensor based on NASICON and NO oxidation catalysts for detection of total NOx in atmospheric environment, Solid State Ionics. 136-137 (2000) 583–588. doi:10.1016/S0167-2738(00)00341-6.

34 N. Miura, G. Lu, M. Ono, N. Yamazoe, Selective detection of NO by using an amperometric sensor based on stabilized zirconia and oxide electrode, Solid State Ionics. 117 (1999) 283–290. doi:10.1016/S0167-2738(98)00423-8.

35 S. Saponara, E. Petri, L. Fanucci, P. Terreni, Sensor Modeling, Low-Complexity Fusion Algorithms, and Mixed-Signal IC Prototyping for Gas Measures in Low-Emission Vehicles, Instrumentation and Measurement, IEEE Transactions on DOI - 10.1109/TIM.2010.2084230. 60 (2011) 372–384.

36 Katulski, R.J.; Namieśnik J.; Stefański, J.; Sadowski, J.; Wardencki, W.; Szymańska, K. «Mobile Monitoring System For Gaseous Air Pollution», Metrology And Measurement Systems Xvi, Nº. 4 (2009): 667-682.

37 M. Gerboles, D. Buzica, Evaluation of Micro-Sensors to Monitor Ozone in Ambient Air, Joint Research Center for Environment and Sustainability. (2009).

38 Helm, I., Jalukse, L. & Leito, I., 2010. Measurement Uncertainty Estimation in Amperometric Sensors: A Tutorial Review. Sensors, 10(5), pp.4430–4455.

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though a high load resistance or amplifying gain is used. The price of OEM amperometric sensors is generally about 100 €.

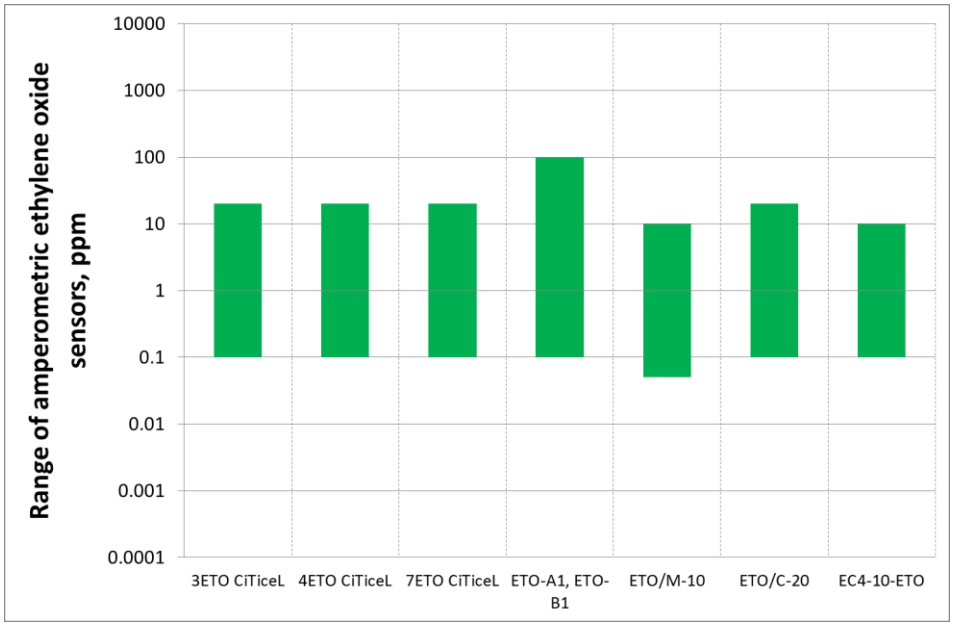

Figure 5: Dynamic range of amperometric sensors of OEMs

Note that the dynamic range shown is based on the manufacturers' specification, and is not estimated in a uniform way by different manufacturers. Also remark that a sensor may be very useful outside its specified range by using a non-linear calibration function.

Table 3: Sensitivity response time and limit of detection of the commercially available amperometric sensors

Model	Manufacturer	limit of detection, µmol/mol	Sensitivity µA/µmol/mol	Selectivity, known interference	Stability (drift), µmol/mol	range µmol/mol	response time, s
3ETO CiTiceL	City Technology	0.1 (Resolution)	2.75 ± 0.5	CO, HC, and VOCs	Zero drift: 2 Baseline drift: 0 – 1 Span drift: < 5%/year	0 - 20	< 140
4ETO CiTiceL	City Technology	0.1 (Resolution)	1.9 ± 0.5	VOCs in general	Zero drift: 4 Baseline drift: 0 - 3 Span drift: < 5%/year	0 - 20	< 120
7ETO CiTiceL	City Technology	0.1 (Resolution)	2.25 ± 0.65	Ethanol≈55%; Methyl-ethyl-ketone≈10%; Toluene≈20%; CO ≈40%	Zero drift: 2 Baseline drift: 0 - 1 Span drift: < 5%/year	0 - 20	< 140
ETO-A1	Alphasense LTD	0.1	2.0 to 3.2	The bias voltage of is set for Ethylene Oxide but needs adjusting for other VOCs.	No data	0- 100	<150
ETO-B1	Alphasense LTD	0.1	2.0 to 3.2		No data	0- 100	<150
ETO/M-10	MembraporAG	0.05 (Resolution)	2.0 +- 0.5		Zero drift: no data, Baseline drift: 0 - 1 Span drift: < 2 %/month	0 – 10	< 140
ETO/C-20	Membrapor AG	0.1 (Resolution)	2.5 +- 0.6	Interference evaluated for a list of VOCs		0 – 20	< 140
EC4-10-ETO	SGX Sensortech	0.1 (Resolution)	1.9 ±0.8	CO,HC, and VOCs	Zero drift: -0.2-2.5 µA Baseline drift: 0-2 Span drift: < 2 %/month	0-10	< 120

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3.3.3 Literature survey

A few articles can be found regarding potentiometric sensors which uses electrolyte (e.g. NASICON) [39, 40, 41, 42, 43]. These papers both gives mechanism of reaction and insight for improvement of this technology. However, all these sensors exhibit a limit of detection in low µmol/mol range or sub-µmol/mol for the best ones. They remain far from our objective of low nmol/mol, high pmol/mol limit of detection.

Knake et al., [44] presented the direct amperometric detection of low levels of formaldehyde in the gas phase with an acidic electrochemical cell based on a gold coated Nafion membrane as working electrode. The sensor was found to show a linear response with a limit of detection of 13 nmol/mol up to and a full scale of 10 µmol/mol. It suffered from a face effect wind and humidity. Cross sensitivities from a number organic and inorganic gases were evidenced. The interferences from NO, NO_2 and SO_2 was corrected using an aluminium oxide filter on which formaldehyde was selectively adsorbed. By forming the difference for the measurements with and without filter a clear signal for formaldehyde could be obtained in presence of the interfering compounds.

Sekhar and Subramaniyam [45] presented a set of 3 electrochemical mixed potential gas sensors for the detection of Benzene, Toluene, Ethylbenzene and Xylenes. The sensor configuration made from Strontium doped Lanthanum Chromite ($La_{0.8}Sr_{0.2}CrO_3$, abbreviated as LSCO) electrode and platinum (Pt) electrode with Yttria-Stabilized Zirconia electrolyte exhibited maximum sensitivity and selectivity to BTEX. The detection limit using mixed potential tape cast sensor was found to be better than 0.5 µmol/mol. For all the sensors, the mixed potential was found to vary linearly with BTEX concentration. The use of a cold-wall set-up and heterogeneous catalysis studies were considered to decrease the BTEX detection limits to nmol/mol levels.

3.4 Resistive sensors

3.4.1 Principle

The transducer mechanism sensor of these devices consists on a metal oxide that changes its electrical properties when exposed to different ambient gases. In commercial sensors the overwhelming property measured in metal oxide sensors is the resistance or conductivity. The tin oxide (SnO_2) is the most used because it has a wide reactivity and strong changes on resistance. The model widely accepted is that tin oxide form grains and the boundary of those grains dominate the conductivity. In presence of an oxidizing gas, normally oxygen in ambient air, the gas molecules react with the tin oxide trapping electrons of the surface creating a positive charge space that act as a barrier for the conductivity.

The sensors are usually small with a size around a dozen millimeters and a weight about a few grams. The sensors need high temperature for the reactions to take place in a faster rate so usually a heater is incorporated into the sensor. The resistive sensors respond to a wide range of concentrations on the gases: from a few nmol/mol on volume in some gases like NO_2 [46] to several thousand of µmol/mol for other gases [47]. However the signal to noise specification provided by the manufacturers of the sensors is usually not very clear and

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39 , Kida, T., Minami, T., Yuasa, M., Shimanoe, K., Yamazoe, N., 2008. Organic gas sensor using BiCuVOx solid electrolyte. Electrochemistry Communications 10, 311–314. doi:10.1016/j.elecom.2007.12.013

40 Kida, T., Minami, T., Kishi, S., Yuasa, M., Shimanoe, K., Yamazoe, N., 2009. Planar-type BiCuVOx solid electrolyte sensor for the detection of volatile organic compounds. Sensors and Actuators B: Chemical 137, 147–153. doi:10.1016/j.snb.2008.12.014

41 Mori, M., Nishimura, H., Itagaki, Y., Sadaoka, Y., Traversa, E., 2009. Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air. Sensors and Actuators B: Chemical 143, 56–61. doi:10.1016/j.snb.2009.09.001

42 Mori, M., Nishimura, H., Itagaki, Y., Sadaoka, Y., 2009. Potentiometric VOC detection in air using 8YSZ-based oxygen sensor modified with SmFeO3 catalytic layer. Sensors and Actuators B: Chemical 142, 141–146. doi:10.1016/j.snb.2009.07.026

43 Kida, T., Morinaga, N., Kishi, S., An, K.-M., Sim, K.-W., Chae, B.-Y., Kim, J., Ryu, B.-K., Shimanoe, K., 2011. Electrochemical detection of volatile organic compounds using a Na3Zr2Si2PO12/Bi2Cu0.1V0.9O5.35 heterojunction device. Electrochimica Acta 56, 7484–7490. doi:10.1016/j.electacta.2011.06.108

44 Knake, R., Jacquinot, P. & Hauser, P., 2001. Amperometric detection of gaseous formaldehyde in the ppb range. Electroanalysis, 13(8-9), pp.631–634.

45 Sekhar, P.K. & Subramaniyam, K., 2014. Detection of Harmful Benzene, Toluene, Ethylbenzene, Xylenes (BTEX) Vapors Using Electrochemical Gas Sensors. ECS Electrochemistry Letters, 3(2), pp.B1–B4.

46 T. Kida, A. Nishiyama, M. Yuasa, K. Shimanoe, N. Yamazoe, Highly sensitive NO2 sensors using lamellar-structured WO3 particles prepared by an acidification method, Sensors and Actuators B: Chemical. 135 (2009) 568–574. doi:10.1016/j.snb.2008.09.056.

47 R.J. Katulski, J. Namiesnik, J. Stefanski, J. Sadowski, W. Wardencki, K. Szymanska, Mobile monitoring system for gaseous air pollution, Metrology and Measurement Systems. 16 (2009) 667–682.

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none of the manufacturers have methods to deal with the mixture problems and usually just provide tables of the equivalent gas concentration cross sensitivity to other gases. The gas desorption tends to be very slow, increasing a lot the amount of time required to make a measurement. The times can be as high as 45 minutes [48] but in most of the cases their response time is in the range of the few minutes [47]. This kind of sensors present the most cross sensitivity of all the reviewed sensors. They react to nearly any volatile compound present on the air, reducing, oxidizing, toxic gases like NOx, or volatile organic compounds (VOC). To improve their selectivity, manufacturers incorporate different dopants or filters. Temperature and humidity are important interferent of the responses and have to be controlled or measured with precision so they can be extracted to provide a model of their influence. The stability is probably the worst problem of this kind of sensors. The response changes over time and the sensors needs to be recalibrated. Manufactures do no provide much information about the drift or stability.

They are generally compact, low cost and higher power than PIDs. MOx sensors also respond to inorganic gases, so one should not use them to measure low concentrations of VOCs where gases such as NO, NO_2 or CO are present in higher concentrations. Thus, when using MOx sensors, information about long term stability, cross sensitivity to gaseous interfering compounds and humidity sensitivity is also important in order to correct sensor response to ensure sufficient accuracy. MOx sensors are advisable if the user is looking for high sensitivity, in particular to VOCs that are not measured by PID (ie many CFCs), more accuracy or cross sensitivity, MOx sensors may provide a possible solution.

Several authors propose a few models for the sensor response:

$$G - G_0 = a \cdot p^b \qquad \textbf{Eq. 1}$$

where G is the conductivity, G_0 is the conductivity at zero gas concentration, p is the gas concentration and a and b are constants [49]. Other methods use the Schotty expression to describe the conductivity of the response [50]. But there is also the possibility to extract temporal parameters from the response curves, such as integral of the response curve [51] or other methods like extracting parameters by methods like Principal Component Analysis from the curves of resistance after a change of temperature [49]. Other authors use non-parametric methods such as neural networks, [47] linear partial least squares (PLS) and spline fitting of the data [49] or even decomposition in functions such Bessel decomposition [52] Fourier or wavelet expansions [53].

Studies show that the most sensitive oxides (high response value) for VOCs include four types: WO_3, SnO_2, In_2O_2 and ZnO [54, 55, 56].

MOx gas sensors in general respond to a large variety of gases. Nevertheless, since complex gas mixtures may contain very high concentrations of interfering gases compared to the low concentrations of the target compounds, the typical lack of intrinsic selectivity of these metal oxide gas sensors remains the limiting factor for possible mass production of these detection systems. So far, different methods have been exploited to improve the selectivity of SnO_2 gas sensors. As an example, we can quote the use of physical or chemical

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48 M.N. Abbas, G.A. Moustafa, W. Gopel, Multicomponent analysis of some environmentally important gases using semiconductor tin oxide sensors, Analytica Chimica Acta. 431 (2001) 181–194. doi:doi: 10.1016/S0003-2670(00)01222-8.

49 H. Kohler, J. Röber, N. Link, I. Bouzid, New applications of tin oxide gas sensors: I. Molecular identification by cyclic variation of the working temperature and numerical analysis of the signals, Sensors and Actuators B: Chemical. 61 (1999) 163–169. doi:doi: 10.1016/S0925-4005(99)00286-5.

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52 A. Vergara, E. Martinelli, R. Huerta, A. D'Amico, C. Di Natale, Orthogonal decomposition of chemo-sensory cues, Sensors and Actuators B: Chemical. 159 (2011) 126–134. doi:doi: 10.1016/j.snb.2011.06.060.

53 M. Aleixandre, I. Sayago, M.C. Horrillo, M.J. Fernández, L. Arés, M. García, et al., Analysis of neural networks and analysis of feature selection with genetic algorithm to discriminate among pollutant gas, Sensors and Actuators B: Chemical. 103 (2004) 122–128. doi:10.1016/j.snb.2004.04.044.

54 Kadosaki M, Terusawa T, Tanino K, Tatsuyama T. Exploration of highly sensitive semiconductor materials to indoor air pollutants. Trans IEE Japan 1999;119:383–389.

55 Kadosaki M, Yamazaki S, Fujiki S, Tanino K, Tatsuyama T. Development of SnO2 -based gas sensors for detection of volatile organic compounds. TransIEEJ 2001;121:395–401.

56 Kadosaki M. Development of a VOC sensor as a countermeasure to sick house syndrome. Ceramics 2003;38:439–443.

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filters [57,58], the doping of the sensitive element [59,60], the combination of several detection systems on the same matrix (electronic noses) [61,62,63] or the operation of sensors under different temperatures [64] or in dynamic regime [65].

3.4.2 Commercially available sensors

A lot of MOx sensors for VOC are comercially available: AMS (S) iAQ-100, iAQ-2000, iAQ-engine and AS-MLV, Unitec (I) SENS 3000 or SENS-IT, UST (D) GGS-1330T, UST-3330T, UST 8330T, SGX SensorTech (CH) MICS-5121, MICS-5521 and MICS-VZ-87, Figaro (J) TGS 2201, 2600, 2602, 8100 and 822, FIS (J) SP3_AQ2 and Synkera Technologies (USA) VOC Sensor (P/n 731). Their charateristics are listed in Table 4 and Figure 6. A modified version of the Aeroqual VM with reduced limit of detection has been included in Appendix III: Review of sensor specifications and data sheets). As for amperometric sensors, the MOx sensors appear to give a limit of detection that is too high for air quality monitoring with the best value reaching 100 nmol/mol (see Figure 6) except for Unitec SENS3000 even though the tests of this sensor carried out by USA Environmental Protection Agency did not reach the level of sensitivity claimed by the manufacturer (see paragraph 4).

Among the Figaro sensors (Figaro Engineering – Jap), the majority of sensors are designed for high concentration of gas compounds, generally over 1 µmol/mol. The most suitable Figaro sensors for VOC monitoring consist of the TGS 2600 (for i-butane and methane), TGS 2602 (for toluene), TGS 2201 (for i-butane and methanol). The TGS 8100 exhibits similar results as TGS 2600 and 2602 while the dimension and power consumption is reduced. These sensors are included in the review in Appendix III: Review of sensor specifications and data sheetsAppendix II: Performance indicators of commercially available sensors extracted from sensors' data sheet.

The responses of Figaro sensors are generally presented with a linear plot with logarithmic axis of Rs/R_0 versus concentration showing that Eq. 1 can be rewritten in a simplified form as in Eq. 2 and Eq. 3:

$$log_{10}\frac{R_s}{R_0} = a + b\ log_{10}p \qquad \text{Eq. 2}$$

$$\boldsymbol{p = \left(\frac{R_s}{R_0}\mathbf{10^{-a}}\right)^{\frac{1}{b}}\ \text{or}\ p = \sqrt[b]{\frac{R_s}{R_0}\mathbf{10^{-a}}}} \qquad \text{Eq. 3}$$

Where Rs is the sensor resistance in displayed gases at the measured concentrations c and Ro is the sensor resistance in clean air. The advantage of using these equations is that the sensos respons has a linear relationship with the analyte while the major drawback is the huge estimation error due to the logarithmic law.

The ETL2000 measurement device, a sensor platform mounting Sens3000 sensors and manufactured by UNITEC (IT) with thick-film MOx sensor for benzene has been evaluated during a 7 week measurement campaign at an urban background location[66]. 15 minute averages from the ETL2000 were compared with the measurements from an AirmoBTX 1000 reference analyzer. The ETL2000 was able to reproduce the concentration distribution within the higher value range. Within the range of up to approximately 3µg/m³ concentration, a decrease of sensitivity and selectivity was observed. The ETL2000 may be an alternative for

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more expensive reference measurement methods in places where the expected benzene concentrations are rather high. The price of MOx sensors is generally about 50 € with some exceptions for sophisticated systems.

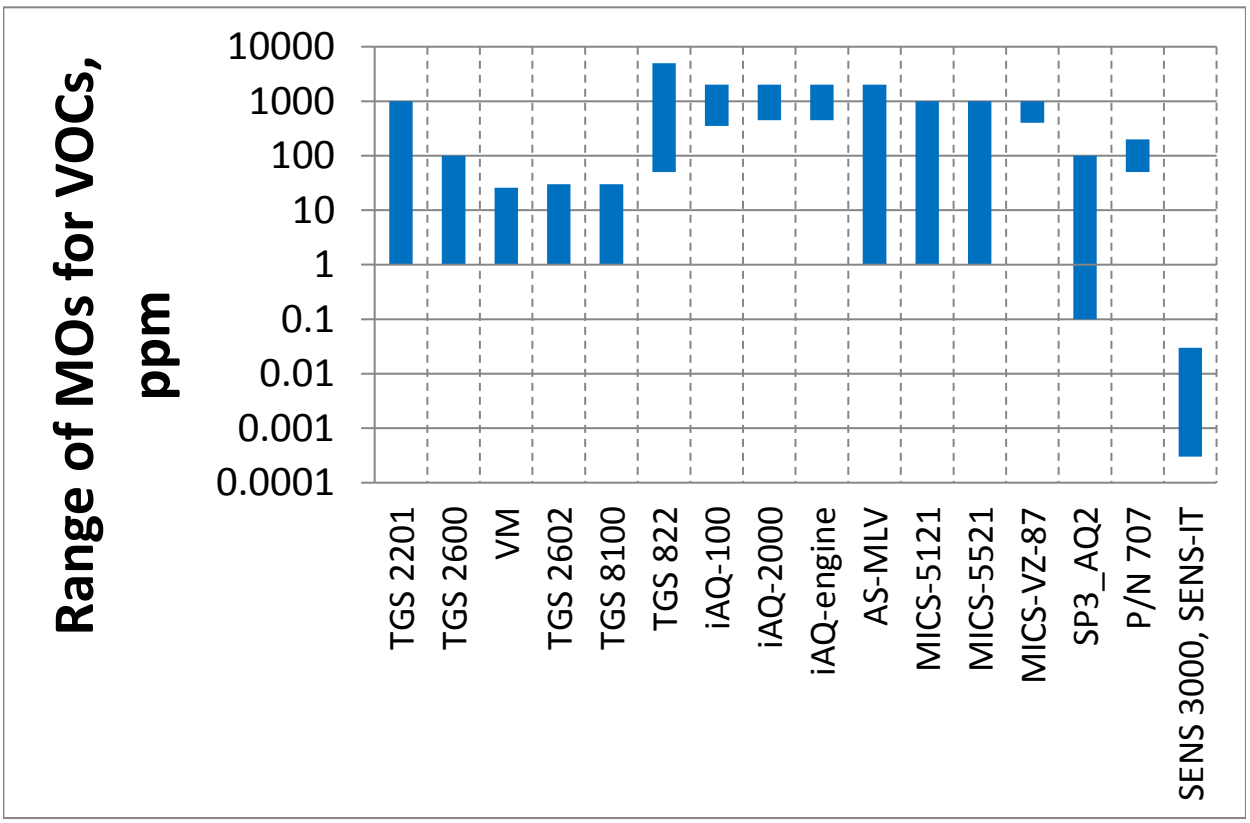

Figure 6: Dynamic range of MOx sensors of OEMs

Note that the dynamic range shown is based on the manufacturers' specification, and is not estimated in a uniform way by different manufacturers. Also remark that a sensor may be very useful outside its specified range by using a non-linear calibration function.

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Table 4: Sensitivity response time and limit of detection of the commercially available MOx sensors

Model	Manufacturer	Limit of detection, µmol/mol	Sensitivity log(Rs/R0)/log(µmol/mol)	Selectivity (interfering gaseous compounds)	Stability (drift)	range, µmol/mol	Resp. time, s
VM	Aeroqual	Resolution: 0.001	No data	Oxidising gases cause a negative response. Combustible gases cause a positive response.	No data	0-25	60
iAQ-100	AppliedSensor Sweden AB	VOC + CO2 equivalents: 350	No data	Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data	VOC + CO2: 350-2000	15 min
iAQ-2000		No data	No data			CO2: 450-2000	15 min
iAQ-engine		CO2 equivalents: 450	No data			CO2 450-2000	15 min.
AS-MLV		No Data. about 1 on graph	No data			CO2: 450-2000	seconds
TGS 2201	FIGARO USA	i-butane: < 1	i-butane: -0.26	CO, H2, CH3OH, other HC, with similar sensitivity, NO2, SO2 and H2S at a different load resistance	No data	i-butane: 2-100	No data
TGS 2600		i-butane: < 1	i-butane: -0.24	CH4, CO, i-butane, Ethanol, acetone, H2		i-butane: 1 - 100	
TGS 2602		toluene: < 1 (likely 0.1)	Toluene: -0.6			toluene: 1-30	
TGS 8100		toluene: < 1 (likely 0.1)	i-butane: -0.14			i-butane: 1-30	
TGS 822		Benzene: < 50	Benzene: -0.67	CH4, CO, i-butane, n-hexane, Ethanol, acetone		Benzene: 50-5000	
SP3_AQ2	FIS	< 1	CO: -0.4	VOCs	No data	EtOH: 0.1 to 100 µmol/mol	No data
MICS-5121/5521	SGX Sensortech	No data	CO: -0.59	reducing gases such as CO, hydrocarbons and VOCs	No data	CO: 1-1000	No data
MICS-VZ-87		No data	CO: -0.59	Volatile Organic Compounds and equivalent CO2		CO2 equivalent: 400 - 1000	15 min
GGS 1330T,	UST Umwelt-sensortechnik	No data	CH4: -0.186	H2 and CO	No data	CH4:-0 - 1000	No data
GGS 2330T		No data	C0: -0.361	CH4 hydrogen and alcohol		CO: 0 - 1000	
GGS 3330T		No data	CH4:-0.227	C1- C8 hydrocarbon, CO and H2		CH4:-0 - 1000	
GGS 8330T		No data	EtOH: -0.227	CH4, CO and H2		EtOH: 0 - 1000	
VOC Sensor (P/n 731)	Synkera Technologies	No data	EtOH: -1.166	Isobutylene (200%), CO (30%), H2 (10%), CH4 (2%), NO2 Negative Resp. Formaldehyde (0%),		EtOH: 75-700	<60
SENS 3000, SENS-IT, ETL2000	Unitec Srl	0.1 µg/m³!	No data	No data	<2.5% / 6 months	Benzene: 0-0.030!	<3!

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3.4.3 Literature survey

In 2002, Mabrook and Hawkind [67] developed a sensor which sensitive material made of titanium dioxide dispersed in poly(vinylidenfluoride) was shown to be sensitive to benzene at room temperature according to the applied voltage. At high voltage the relative resistance of the films increased linearly (r = 0.92) with benzene concentrations resulting in a detection limit of 10 µmol/mol.

In 2005, Tamaki [68] presented a review for MOx sensors in which VOCs were cited in a few articles. The lowest limit of detection (1-3 nmol/mol for BTX) was attained using an Au-SnO_2 MOx sensor heated at 400 °C combined with pre-concentration [69] (micro-GC). Without pre-concentration, a Pd-WO_3 sensor heated at 400 °C was reported to be able to measure between 10 and 1000 nmol/mol of aromatics [70]. Other references for MOx sensors including WO_3-SnO_2, CuO-SnO_2, $SmFeO_3$, Ti-W-O and Pt/Al203-WO_3, reported measurement capacity over 1000 nmol/mol that are not relevant in this review.

The Figaro TGS 2600, a TiO_2 MOx sensor has been successfully implemented for methane monitoring in a remote area in Alaska [71]. Satisfactory results were attained using comparison of the sensor responses to a Fast Methane Analyzer FMA 100 (Los Gatos Research, CA, USA) after removal of the strong sensitivities for temperature and relative humidity. This correction of sensitivity increased the absolute accuracy required for in-depth studies, and the reproducibility between two TGS 2600 sensors run in parallel was very good.

In 2009, Ke et al. [72], developed MEMS-based benzene gas sensor consisting of a quartz substrate, a thin-film WO_3 sensing layer, an integrated Pt micro-heater and Pt interdigitated electrodes (IDEs). The sensing process used the oxidation on the heated WO_3 sensing layer caused by benzene which lead to changes in the electrical resistance between the IDEs. At an optimal working temperature of 300 °C, the sensor had a high degree of sensitivity, a detection limit of 0.2 µmol/mol and a rapid response time (35 s).

Wen et al [64] developed a SnO_2 –TiO_2 based sensor doped with Ag ion powder prepared using the sol–gel method. The authors showed how the sensor can exhibit remarkable selectivity to each VOCs by tuning the voltage of the heater and hence the operating temperature of the sensor. Further investigations based on quantum chemistry calculation showed that the difference of orbital energy of VOCs molecule may be a qualitative factor to affect the selectivity of the sensor. In this paper, the ratio of resistance (R0) in air to that in the tested gas (R) was found to be about 60 for a mixture of 200 µmol/mol of ethanol. Setting that the limit of detection would correspond to a R/R0 ratio higher than 3 and assuming linearity between R and ethanol level, the limit of detection would be about 10 µmol/mol (equal to 200 / 60 x 3). However, this value is indicative since R and gas pollutant show generally a logarithmic relationship that would result in a lower detection limit. However, the main interest of the author was to demonstrate the improvement in selectivity rather than the best sensitivity.

In 2010, Zeng et al. [73] demonstrated and explained the mechanism behind the improvement of sensitivity for VOCs monitoring in indoor air by adding TiO_2 dopant to SnO_2 sensors. The paper focus on the explanation of the improved sensitivity rather than estimating the limit of detection of the sensor. Similarly, Kadosaki et al. [74] looked at the most suited oxide materials among WO_3, SnO_2, In_2O_2 and ZnO for total volatile organic compounds (TVOC) measurements in indoor air. The authors showed that SnO_2 and more clearly WO_3, were the most sensitive oxide materials within the tested ones and that halogenated hydrocarbons (chloroform, dichlorobenzene, etc). Among oxy, halogenated, aromatics, aliphatic hydrocarbons, terpenes, esters and aldehydes, the halogenated and aliphatic hydrocarbons gave the lowest responses using any of the oxide materials. For the aromatic hydrocarbons, higher sensitivity (up to 4 times more) was found for compounds

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with functional groups (methyl groups) added to simple rings or double bonds both for SnO_2 and WO_3 sensors: higher response for terpenes, toluene, xylenes, ethylbenzene, styrene and trimethyl benzene than for benzene. However, the authors concluded that a simple SnO_2 or WO_3 sensor is not able to detect nmol/mol levels of VOCs. They investigated the addition of noble metals to improve sensitivity of SnO_2 or WO_3 sensors.

Best results were obtained by addition to SnO_2 sensors of Ag for heptanes, Au on for toluene plus heptane and Pd for toluene and trichloroethylene on WO_3 sensors and Au for toluene, Pt for heptane and trichloroethylene and Pd for trichloroethylene and other halogenated hydrocarbons. The addition of noble metals had smaller effect on In_2O_2 and ZnO sensors than on SnO_2 or WO_3 sensors. The authors studied the effect of Pt and Pd optimal amount, size of dopant and temperature heater for the highest response of the SnO_2 sensor to halogenated and aliphatic hydrocarbons. In conclusion it was shown that for some compounds a 15-fold increase in sensitivity could be reached according to the additive composition, film size and according to the temperature of the sensor heater. Strangely enough the authors did not study the optimisation of WO_3 sensors that seemed to be more sensitive than SnO_2 sensors. In this paper, the ratio of resistance (R0) in air to that in the tested gas (R) was found to be about 6 for a mixture of 1 µmol/mol of toluene for a SnO_2 sensor operated at 250 °C with 0.5 wt% of Pt and 0.5 wt% of Pd . Setting that the limit of detection would correspond to a R/R0 ratio higher than 3 and assuming linearity between R and toluene level, the limit of detection would be about 0.5 µmol/mol (equal to 1 / 6 x 3). However, this value is indicative since R and gas pollutant show generally a logarithmic relationship that would result in a lower detection limit. However, the main interest of the author was to demonstrate the improvement in selectivity rather than the best sensitivity.

Metal oxide semiconductor (MOx) gas sensors generally respond to a large variety of gases. To achieve selectivity the well-established temperature cycled operation (TCO) can be used [75]. The signal output of TCO can be seen as a virtual sensor array providing multichannel information. Data are tipically processed by discrimination and quantification algorithms like e.g. linear discriminant analysis (LDA) and partial least square regression (PLS) [76].

Table 5: Research study of MOx sensors for the measurement of benzene or other VOCs

Reference	Target gas	Sensitive layer	Limit of detection, µmol/mol	Response time	Sensitivity factor, (µmol/mol.min)	Year
Elmi et al. [69]	BTX	Au-SnO2 MOx sensor + pre-concentrator	1 - 3	-		2001
Mabrook et al. [67]	Benzene	TiO_2.	10	35 s	5.833	2002
Kanda [77].	Aromatics	Pd-WO3 sensor heated at 400 °C	0.010 - 1.000			2004
Ke et al. [72]	Benzene	WO_3.	0.2	20 s	0.066	2009
Wen et al.[64]	methanol, ethanol, acetone and formaldehyde VOCs)	SnO_2 - TiO_2 doped with Ag	For ethanol about 10	20 s	0.075	2010
Zeng et al. [73]	methanol, ethanol, formaldehyde, and acetone (VOCs)	SnO_2 doped with TiO2	A few 10s of µmol/mol	10-20 s		2010
Kadosaki et al. [74]	TVOC (response to 27 VOCs typical for indoor air)	SnO_2 doped with TiO2	toluene: 0.5 trichloroethylene: 0.2	No data		2010

Commercial sensors using TCO have been shown in laboratory studies to detect toxic VOC in the nmol/mol range [78]. Some sensor manufacturers provide information on TCO parameters in their data sheet e.g. Figaro Engineering for the detection of CO (TGS-2442) but in most case the specific use of TCO is implemented by sensor system manufacturers [79]. Sensor systems for VOC detection based on TCO have been reported from

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several companies e.g. 3S GmbH (DE) and NanoSense (FR). The TCO mode may be also applied to Silicon Carbide Feld Effect Transistors (SiC-FET) that allows to reach sub-nmol/mol sensitivity likely keeping the selectivity through the use of LDA and PLS statistical methods [80] and [81].

3.5 Spectroscopic method

Allouch et al. [82] reviewed recent research studies for optical and colorimetric-based portable devices for high sensitive and real time BTEX analysis. Within all instruments included in this review, only two systems were suitable for the low nmol/mol range. The first type of system used a micro-fluidic UV portable spectrometer with a silicate absorbent and later thermal desorption which resulted in a limit of detection of about 10 nmol/mol for hourly values [83]. The system was further improved to reach a limit of detection of about 1 nmol/mol for 30-min averages whilst resulting in a more complicated setup including a pulse pump system and new detection cell [84]. The second type of instrument [85] was based on the variation of the reflected light intensity when BTEX gases are present in a detection tube which contains an optical fiber coated with a polymeric sensitive film. The change in the intensity is proportional to the amount of BTEX present inside the tube. The sensor design is composed of a concentration system (12 cm length) and a detection cell (7.2 cm length). BTEX were injected as liquid into the injection cell that vaporizes on heating. Gaseous BTEX were then transmitted to the glass tubing that contains a PDMS (polydimethysiloxane) layer for the adsorption and desorption processes and finally to the detection tube that contained the coated sensitive film optical fiber. A thin film of polysiloxane, deposited by uniform spray coating technology had been used for this sensitive film. The most convincing results have been obtained at a diode wavelength of 650 nm and a sampling time of 25 min at 200 ml/min. They have been checked using a gas chromatography-flame ionization detector (GC-FID). The detection limit was found to be around 2.5 nmol/mol for benzene without the need for a pre-concentration step. Despite the fast, real-time and on-site monitoring of BTEX provided by this sensor, it is still chemicals consuming. In addition, polymer-based sensing is limited in terms of durability.

Maruo et al, [86] developed a portable device for formaldehyde monitoring aiming at a simple and inexpensive sensor. It is based on specific colorimetric reaction between formaldehyde and a β-dikétone in a glass substrate where it remains stable for a long time. The sensor system includes two LED light sources and two photo-diode to measure the absorbance of the lutidine derivative formed in the substrate at two wavelength in order to correct the temperature/humidity effects of the absorption mechanism. The absorbance difference of the sensor element was measured in the monitoring device at regular intervals of, for example, one hour or 30 min, and the result was converted into formaldehyde concentration. The detection limit was found to be 10 µg/m³ for a 30 min sampling.

3.6 Portable miniaturized and micro gas chromatographs

Portable gas chromatographs used for the determination of VOCs in air quality assessment can be classified into miniaturized chromatographic systems (µGC), micro Gas Chromatographs or lab-on-a-chip type (LOC)) and portable gas chromatographs analyzers.

Low power consumption sample processing, column programming, detection systems and data handling have been combined to reduce the size and weight of GCs for portable use. The simplest may consist of little more than an ambient temperature injector, column, and detector, while the most complex may have every feature of an advanced laboratory instrument. Portable GCs may be based on semiconductor chip processing or assembled from discrete components

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81 C. Bur et al., Discrimination and Quantification of Volatile Organic Compounds in the ppb-Range with Gas Sensitive SiC-Field Effect Transistors, Procedia Eng., vol. 87, pp. 604–607, 2014.

82 Allouch, A., Le Calvé, S., Serra, C.A., 2013. Portable, miniature, fast and high sensitive real-time analyzers: BTEX detection. Sensors and Actuators B: Chemical 182, 446–452. doi:10.1016/j.snb.2013.03.010

83 Horiuchi, T. et al., 2006. Portable Aromatic VOC Gas Sensor for Onsite Continuous Air Monitoring with 10-ppb Benzene Detection Capability. NTT Technical Review, 1, p.30–.37

84 S. Camou, T. Horiuchi, and T. Haga, "Ppb Level Benzene Gas Detection by Portable BTX Sensor Based on Integrated Hollow Fiber Detection Cell," Proc. of IEEE Sensors 2006, Daegu, Korea, 2006.Camou, S., Tamechika, E. & Horiuchi, T., 2012. Portable Sensor for Determining Benzene Concentration from Airborne/ liquid Samples with High Accuracy. NTT Technical Review, 10(2), pp.1–7.

85 Silva, L.I.B. et al., 2009. Polymeric nanofilm-coated optical fibre sensor for speciation of aromatic compounds. International Journal of Environmental Analytical Chemistry, 89(3), pp.183–197.

86 Maruo, Y.Y., Nakamura, J., 2011. Portable formaldehyde monitoring device using porous glass sensor and its applications in indoor air quality studies. Analytica Chimica Acta 702, 247–253. doi:10.1016/j.aca.2011.06.050

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3.6.1 Principle of Portable and Micro Gas Chromatographs

Micro Gas Chromatographs (µGC) combine micro GC columns with either PID or MOx sensors. The first miniaturized GC, created by Terry et al. at Stanford University in 1975, was fabricated on a silicon wafer using photolithography and chemical-etching techniques [87]. The µGC included an injection valve and used an internally mounted thermal conductivity detector. The 1.5 m long, 40 µm deep, 200 µm wide column had a rectangular cross-section. Difficulty in evenly coating rectangular channels and in miniaturizing the other GC components meant that the resolving power of the column was poor compared with modern standard columns. Another review [88] looked after the pre-concentration step needed to decrease the limit of detection of VOC sensors.

The ion mobility spectrometer (IMS) can be considered as a sub-class of chromatographic separators. The principle of every IMS is a time-of-flight measurement. After a gaseous sample has entered in the spectrometer it will be ionized by a radioactive source. The resulting positive and negative charged species will be accelerated over a short distance and their time-of-flight will be determined. The IMS is different than the mass spectrometer in that it operates under atmospheric conditions and does not need large and expensive vacuum pumps. Because of this, IMSs can be easily miniaturized.

3.6.2 Commercially available sensors

In this category, we can find:

- The Person-Portable GC/MS of INFICON models Explorer Portable GC, HapSite ER and HapSite smart/smart plus [89,90]
- an automated vapor sampling with transfer line between a gas chromatograph and a ion mobility spectrometry (IMS) the Environmental Vapor Monitor (EVM II) of Femtoscan [14],
- a portable gas chromatograph with 3 columns at 40-80 °C, PID sensor (10.6 eV) and internal cylinder for Ultra High Purity N2/Zero Air as carrier gas, the INFICON model Explorer Portable Gas Chromatograph [91]
- and a portable GC as the Defiant Technologies model Frog 4000.

These instruments reach the desired sensitivity and selectivity (Table 6). However, the price of such instruments (between 15k-100k€) limit their applicability. The Bentekk (DE) measurement device [92] is a promising portable gas chromatograph coupled with photo ionization detection. It can selectively analyze more than VOCs within 30 seconds. The instrument does not need external carrier gas and it weighs about 1 kg. In the current state, the limit of detection is stated as 50 nmol/mol in data sheet, in a personal communication it was given as 25 nmol/mol and the aim of the company is to reduce it to 1.5 nmol/mol (maybe by the end of 2015).

Other instruments consist of the µRAID and the RAID-M100, two IMS portable hand-held detectors are used in the field of military, emergency response and security services. They are manufactured by Brucker [93]. They are able to measure toxic substances in the nmol/mol to µmol/mol range. It is not included in Table 6 because the manufacturer does not provide information related to the monitoring of aromatics in ambient air. The main objective of this instrument seems to be military applications. In 2006, Statheropoulos et al.,[94] conducted a study of acetone in expired air using the EVM II. The limit of detection of acetone with the EVM II was found lower than 100 nmol/mol.

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88 Lahlou, H., Vilanova, X. & Correig, X., 2013. Gas phase micro-preconcentrators for benzene monitoring: A review. Sensors and Actuators B: Chemical, 176, pp.198–210.

89 *http://products.inficon.com/en-us/nav-products/Product/Detail/HAPSITE-ER-Identification-System?path=Products%2Fpg-ChemicalDetection*

90 *http://products.inficon.com/en-us/nav-products/Product/Detail/HAPSITE-Smart-Plus-Chemical-Identification-System?path=Products%2Fpg-ChemicalDetection*

91 *http://products.inficon.com/en-us/nav-products/Product/Detail/Explorer-Portable-Gas-Chromatograph?path=Products%2Fpg-ChemicalDetection*

92 *J. Frank, H. Fischer, G. Matz, Effect of Temperature and Flow variation for a short Multi Capillary Column – PID, poster 860-14 P, presented at PITTCon, Conference and exposition, Philadelphia, 17-21 March 2013*

93 *https://www.bruker.com/products/cbrne-detection/ims/uraid/overview.html*

94 Statheropoulos, M., Agapiou, A., Georgiadou, A., 2006. Analysis of expired air of fasting male monks at Mount Athos. Journal of Chromatography B 832, 274–279. doi:10.1016/j.jchromb.2006.01.017

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Table 6: Sensitivity response time and limit of detection of the commercially available portable gas chromatographic instruments

Model	Manufacturer	limit of detection, µmol/mol	Sensitivity µA/µmol/mol Selectivity	Stability (drift)	range µmol/mol	response time, s
Model 312	PID Analysers	0.0005 for benzene	According to the selectivity of the used columns. Generally this is not a problem for BETX and other VOCs	<1% over 24 hours	0.0005-10000	1
Frog 4000	Defiant Technologies	in the nmol/mol range		No data	nmol/mol range	300
zNose, model 4600	Electronic Sensor Technology	in the nmol/mol range		No data	nmol/mol range	30
Gas Chromatography in your hand	Bentekk	0.025, on-going improvement towards 0.015		No data	No data	30
Explorer Portable GC,	INFICON	0.005		No data	0.005 - 9999	No data
HapSite ER	INFICON	pmol/mol depending on configuration		No data	pmol/mol to µmol/mol	600
HapSite smart/smart plus	INFICON	high pmol/mol depending on configuration		No data	high pmol/mol to µmol/mol	900
model EVM II	FemtoScan	0.539	Separation by GC of alkanes, cyclo-alkanes, alkenes, alcohols, aromatics, ketones, esters	No data	No data	< 30

3.6.3 Literature survey

Sanchez et al., [95] presented a hybrid micro-system to get a sensitive and selective portable device for the detection of VOC in air. Micro-fabrication technology was applied to the development of a gas chromatographic micro-column placed in an oven at 303 °K. This system of separation was positioned upstream of the gas sensor. A complete description of the GC micro-column and of the prototype's architecture is given. It included a simple MOx sensor (Microsens, Neuchatel-CH) whose conductance was measured at 773 °K. The carrier gas consisted of dry N_2 (80 %) and O_2 (20 %). Special attention had to be paid to the pressure of the carrier gas. The gas sample was formed by a gas mixture of benzene, toluene and two isomers of xylene eluted in synthetic air. This prototype, beyond its small size and its great chemical discrimination, provided fast responses and offers best results with very low temperatures of the GC micro-column. No information about the limit of detection or validation is given in this paper apart from the ability to separate synthetic mixtures including BTX. Sensitivity in the sub µmol/mol range was expected with this system.

Zampolli et al, [96,97,98]developed a µGC for the detection of sub-nmol/mol BTEX. The systemic approach includes the study of innovative pre-concentration materials, micromachining of GC components and devices, the fabrication and characterization of complete system prototypes including a pre-concentration unit, separation unit and detection unit. The pre-concentration unit is based on a Micro-Electro-Mechanical System

[95] *Sanchez, J.-B. et al., 2006. A selective gas detection micro-device for monitoring the volatile organic compounds pollution. Sensors and Actuators B: Chemical, 119(1), pp.227–233.*
[96] *Zampolli, S. et al., 2006. A palm-sized gas-chromatographic system for sub-ppb VOC detection in air quality monitoring applications. In 5th IEEE Conference on Sensors, 2006. 5th IEEE Conference on Sensors, 2006. pp. 1163–1166.*
[97] *Zampolli, S., Betti, P., Elmi, I., Dalcanale, E., 2007. A supramolecular approach to sub-ppb aromatic VOC detection in air. Chem. Commun. 2790–2792. doi:10.1039/B703747C*
[98] *Zampolli, S., Elmi, I., Mancarella, F., Betti, P., Dalcanale, E., Cardinali, G.C., Severi, M., 2009. Real-time monitoring of sub-ppb concentrations of aromatic volatiles with a MEMS-enabled miniaturized gas-chromatograph. Sensors and Actuators B: Chemical 141, 322–328. doi:10.1016/j.snb.2009.06.021*

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(MEMS) pre-concentration column packed with an appropriate chemical phase that traps aromatic compounds during sampling. When heated, it injects the pollutant into the separation unit consisting of the MEMS column filled with a commercial stationary phase. The platinum heater and temperature sensor integrated on the GC column allow temperature control and modulation. In the detection unit a MOX sensors array provides the signals when reached by the single separated compounds. The air samples and the on-board generated carrier gas flow are provided by 2 mini pumps and managed by 2 mini valves; fluidic interconnections among the different components are made in stainless steel interconnection blocks. By means of a dedicated software it is possible to manage the whole system and program it for a specific measurement sequence. The prototype is currently been optimized with a PID sensor in order to make it commercially available.

In 2009, a hybrid system for rapid detection and analysis of BTEX was developed by Iglesias et al, [99]. The system combined a selective and sensitive sensing elements with a fast and miniaturized chromatographic separation method. The sensing elements consisted of an array of microfabricated quartz crystal tuning forks modified with selective molecularly imprinted polymers. The separation method uses optimized short columns. The sensitivity and selectivity of the sensing elements together with the help of the separation provided fast detection and analysis of BTEX in real samples containing highly concentrated interfering agents without pre-concentration or heating of columns. The low cost, low power consumption, and small size of the hybrid device were suitable for occupational health, industrial safety, and epidemiological applications. A linear dynamical range from about 5 ppmv and up to 250 ppmv was reported. This work seems to have been continued by Chen et al. [100] to build a wireless hybrid chemical sensor for detection of environmental VOCs with similar sensing principle. The device was wireless, portable, battery-powered, cell-phone operated and it allowed reliable detection in nmol/mol of BTEX in the presence of complex interferents.

In 2010, Hallidays et al. [101] reported the preliminary results of an early development of a planar 2-dimensional GC chip microfabricated system using a PID detector suitable for the separation of volatile organic compounds (VOCs) and compatible for use as a portable measurement device. This low-power device showed good separation performance for a small set of VOCs and promising preliminary results for the separation of µmol/mol gas mixtures of a set of VOCs.

In 2012, Bae et al., [102] presented a portable gas analyzer that consisted of a micro-flame ionization detector (micro-FID) and a µGC. Both components were integrated in a "lunchbox" sized housing with all the peripherals to operate the micro-GC/FID without an external power and gas supply. The total size of this µGC/FID lunch box was 24x20x10 cm^3 with 4 kg mass. An electrolyzer in the lunchbox produced pure hydrogen and oxygen for the micro-FID, eliminating the need for gas tanks on board. The instrument was aimed at analysis in NASA planetary exploration missions, cabin air monitoring in spacecraft or in the international space station. The separation/detection capability of the NASA SMAC list of compounds including Benzene, Toluene, Ethylbenzene, xylenes (BTEX), Methanol, Isoprene, Methylenechloride, Nitromethane, Methylethylketone, Chloroform, 1,2-dichloroethane, 1-butanol, Trichloroethane, 2-ethoxyethanol, 4-methyl-2-pentanone, Hexanal, and Diacetone alcohol was demonstrated. The authors concluded that the instrument would be able to detect VOCs of less than 0.1 µmol/mol concentration levels.

The Edward T. Zellers' research team of the University of Michigan has designed several prototypes of MEMS-µGC for continuous monitoring of VOCs [103]. The MEMS-µGC was adapted for the analysis of low- and sub-

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99 Huang, Guangming, Liang Gao, Jason Duncan, Jason D. Harper, Nathaniel L. Sanders, Zheng Ouyang, and R. Graham Cooks. "Direct Detection of Benzene, Toluene, and Ethylbenzene at Trace Levels in Ambient Air by Atmospheric Pressure Chemical Ionization Using a Handheld Mass Spectrometer." Journal of the American Society for Mass Spectrometry 21, no. 1 (January 2010): 132–35. doi:10.1016/j.jasms.2009.09.018.

100 Chen, Cheng, Francis Tsow, Katherine Driggs Campbell, Rodrigo Iglesias, Erica Forzani, and N.J. Tao. "A Wireless Hybrid Chemical Sensor for Detection of Environmental Volatile Organic Compounds." IEEE Sensors Journal 13, no. 5 (May 2013): 1748–55. doi:10.1109/JSEN.2013.2239472.

101 Halliday, J. et al., 2010. Lab-on-a-chip GC for environmental research. LC GC Europe, 23(11).
Jaydene Halliday, Alastair C. Lewis, Jacqueline F. Hamilton, Christopher Rhodes, Keith D. Bartle, Phillip Homewood, Robin J.P. Grenfell, Brian Goody, Alice Harling, Paul Brewer, Gergely Vargha, Martin J.T. Milton, Lab-on-a-Chip GC for Environmental Research, LCGC Europe, Volume 23, Issue 10, pp. 514-523, Nov 1, 2010, http://academy.chromatographyonline.com/lcgc/article/articleDetail.jsp?id=696156&sk=&date=&pageID=7

102 Bae, Byunghoon, Jihyung Kim, Junghoon Yeom, Qingmei Chen, Curtis Ray, and Mark Shannon. "Development of a Portable Gas Analyzer Using a Micro-Gas Chromatograph/Flame Ionization Detector (micro-GC/FID) for NASA's Environmental Missions." American Institute of Aeronautics and Astronautics, 2012. doi:10.2514/6.2012-3435.

103 Kim, Sun Kyu, Hungwei Chang, and Edward T. Zellers. "Microfabricated Gas Chromatograph for the Selective Determination of Trichloroethylene Vapor at Sub-Parts-Per-Billion Concentrations in Complex Mixtures." Analytical Chemistry 83, no. 18 (September 15, 2011): 7198–7206. doi:10.1021/ac201788q.

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nmol/mol concentrations of trichloroethylene (TCE) vapors in complex mixtures of indoor air contamination. The µGC prototype employed a microfabricated pre-concentration focuser, dual microfabricated separation columns, and a microsensor array. These were interfaced to a non microfabricated front-end pretrap and high-volume sampler module to reduce analysis time and limits of detection (LOD). Selective preconcentration and focusing were coupled with rapid chromatographic separation and multisensor detection for the determination of TCE in the presence of up to 45 interferences. Preconcentration factors as high as 500 000 were achieved. Sensitivities were constant over the range of captured TCE masses tested (i.e., 9 - 390 ng), and TCE was measured in a test atmosphere at 120 pmol/mol, with a projected LOD of 40 pmol/mol (4.2 ng captured, 20 L sample) and a maximum sampling + analytical cycle time of 36 min. Short- and medium-term (1 month) variations in retention time, absolute responses, and response patterns were within acceptable limits. The application of the µGC was demonstrated through laboratory testing. The prototype was then implemented in real case studies of indoor air analysis including validation against reference measurements [104,105] showing low bias (generally within ± 25 %), linearity of the µGC in the range between 4.8 and 77 nmol/mol and a re-evaluated LOD of 52 pmol/mol. A subsequent publication by Bryant-Genevier et al. [106] aimed at improving and applying chemometric methods for use with micro-GC chemiresistor sensor arrays. This paper described the use of hybrid multivariate curve resolution method, which combines evolving factor analysis (EFA) with alternating least squares (ALS), to the analysis of partially overlapping peaks from vapors measured by a microsensor-array gas chromatograph detector. Using calibrated response patterns as inputs for the ALS refinements of EFA-extracted responses, the fidelity of recovered response patterns and elution profiles was sufficiently high to differentiate the composite peak components in 124 of 126 cases (98%) and to quantify them to within ±30% of actual values in 95 of 126 (75%) cases. Recently, Bryant-Genevier [107] published an article describing the development of a highly effective MEMS pre-concentrator focuser to be associated with the µ-GC developed before.

Nasreddine et al., [108] reported on a miniaturized GC/PID system dedicated to BTEX monitoring in near to real time conditions at nmol/mol level for indoor. The system consists of a 6-ports valve, a capillary column and a mini-photoionization detector (PID), its final weight is around 4 kg. The system operates at very low flow rate (lower than 4 $mL.min^{-1}$) irrespective of the carrier gas used. The system's performance was studied and optimized with two different carrier gases, namely hydrogen and nitrogen. The total analysis time for a single run was set to a maximum of 10 min. A detection limit of 1 nmol/mol was found for benzene and toluene with both carrier gases and less than 3 nmol/mol for other compounds of the family.

3.7 Electronic nose and sensors arrays

3.7.1 Principle

Another class of measurement devices consists of sensor arrays, which are devices that contain several simple sensors of different type. Smart pattern recognition software often based on neural networks is used to make the sensor array more specific than the sum of the single sensors it is composed of. Sensor arrays are often part of devices called "electronic noses" or "e-noses". This name is derived from the fact that (part of) their job is to detect odours. An electronic nose, which employs an array of chemical sensors and mathematical pattern recognition algorithms for comparing and recognizing gas samples, can be used for continuous monitoring of multiple chemicals of choice with improved sensitivity. Each element in the sensor array responds to a number of different chemicals or classes of chemicals. The elements of such an array need not be individually highly selective toward any given analyte, instead the collection of sensors should contain as much chemical diversity

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[104] Kim, Sun Kyu, David R. Burris, Hungwei Chang, Jonathan Bryant-Genevier, and Edward T. Zellers. "Microfabricated Gas Chromatograph for On-Site Determination of Trichloroethylene in Indoor Air Arising from Vapor Intrusion. 1. Field Evaluation." Environmental Science & Technology 46, no. 11 (June 5, 2012): 6065–72. doi:10.1021/es204624z.

[105] Kim, Sun Kyu, David R. Burris, Jonathan Bryant-Genevier, Kyle A. Gorder, Erik M. Dettenmaier, and Edward T. Zellers. "Microfabricated Gas Chromatograph for On-Site Determinations of TCE in Indoor Air Arising from Vapor Intrusion. 2. Spatial/Temporal Monitoring." Environmental Science & Technology 46, no. 11 (June 5, 2012): 6073–80. doi:10.1021/es204625w.

106 Bryant-Genevier, Jonathan, Kee Scholten, Sun Kyu Kim, and Edward T. Zellers. "Multivariate Curve Resolution of Co-Eluting Vapors from a Gas Chromatograph with Microsensor Array Detector." Sensors and Actuators B: Chemical 202 (October 31, 2014): 167–76. doi:10.1016/j.snb.2014.05.049.

[107] Bryant-Genevier, Jonathan, and Edward T. Zellers. "Toward a Microfabricated Preconcentrator-Focuser for a Wearable Micro-Scale Gas Chromatograph." Journal of Chromatography A 1422 (November 27, 2015): 299–309. doi:10.1016/j.chroma.2015.10.045.

[108] *Nasreddine, Rouba, Vincent Person, Christophe A. Serra, and Stéphane Le Calvé. "Development of a Novel Portable Miniaturized GC for near Real-Time Low Level Detection of BTEX." Sensors and Actuators B: Chemical 224 (March 1, 2016): 159–69. doi:10.1016/j.snb.2015.09.077.*

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as possible, so the sensor array responds to the largest possible cross-section of analytes. A distinct pattern of responses produced over the collection of sensors in the array can provide a fingerprint that allows classification and identification of the analyte.

The e-nose systems are not expected to be readily applicable for accurate quantative benzene measurement since many of them have another main target application and they are costly. It is reported that cost for an e-nose system ranges from US $20,000 to $100,000 in Europe, the United States, and Japan (Arshak et al., 2004).

3.7.2 Research studies

Lee et al., 2002 [109] presented an array of ten different gas MOs-sensors (SnO_2) integrated on a substrate to identify various kinds and quantities of VOCs, such as benzene, toluene, ethyl alcohol, methyl alcohol, and acetone. The sensor included a platinum heater and was fabricated using silk printing methods on an alumina substrate. The sensors show a high and broad sensitivity and reproducibility to low concentrations based on the use of nano-sized sensing materials with different additives. Utilizing the sensing signals of the array, an artificial neural network with an error-back-propagation learning algorithm is then implemented as a recognition system for classifying and quantifying the VOCs. Simulation and experimental results demonstrated that the proposed gas sensor array with neural network was effective in recognizing various kinds and quantities of VOCs.

Srivastava (2003) [110] showed the possibility of using an array of SnO_2-based thick-film gas sensors for the detection of VOCs indoors and outdoors. A gas chamber of 2.8 L with a liquid chemical injection system was used to check the performance of the SnO_2 sensors doped with Pt, Pd and Au. The responses of the sensor array were transformed based on mean and variance of the individual gas-sensor combination to improve the classification accuracy of neural network classifier. A three-layer feedforward neural network with sigmoidal activation function was used to process the data. A back propagation learning algorithm was used for training. The neural network processing of the transformed data was successful in denitrifying seven VOCs even with noisy data. However, there was no further attempt to quantify the VOCs.

Zampolli et al. used an e-nose to monitor multiple gases other than VOCs [111]. They developed an e-nose with metal oxide sensors on micromachined hotplate arrays. This device is different from the previous e-noses, which utilize cross-sensitivity of non-specific sensor arrays. The first sensor (SnO_2 with operating temperature of 375 °C) was specifically designed for NO_2, while the second was for CO (SnO_2 and SiO_2 sensing materials operated at 400 °C). A commercial RH sensor monitored the relative humidity, which interferes in both CO and NO_2 detection. A neuro-fuzzy system provided by the adaptive fuzzy modeller (AFM) was used to predict concentrations of either NO_2 or CO based on three inputs, i.e., outputs from the CO, NO_2 and RH sensors. A chamber study showed that the device could identify and discriminate concentrations as low as 20 nmol/mol for NO_2 and 5 µmol/mol for CO, which are lower than the IAQ threshold values.

Penza et al. (2005) [112] also reported that sensors coated with nanofilms and nanocomposite can improve sensitivity for organic gases. They fabricated multilayer and nanocomposite sensors by depositing Langmuir-Blodgett (LB) films consisting of tangled bundles of single-walled carbon nanotubes (SWCNTs) onto three different sensing systems, including surface acoustic waves (SAWs), quartz crystal microbalance (QCM), and standard silica optical fibre (SOF). The sensors were simultaneously tested in a test cell of 1 L with an airflow rate of 1 L/min. The six VOC vapours introduced to the test cell were generated by the bubbling method. The vapour pressure of six VOCs were tested in the range of 15 – 150 mmHg (ethanol), 50 – 200 mmHg (methanol), 20-150 mmHg (isopropanol), 100-650 mmHg (acetone), 30-270 mmHg (ethylacetate) and 10-100 mmHg (toluene). They reported good correlation of the sensing mechanisms and refractive index of the sensors. Based on the experiment results, the potential use of multi-sensors based on carbon nanotubes and pattern recognition techniques was suggested for the efficient analysis of VOCs.

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109 Lee, Dae-Sik, Youn Tae Kim, Jeung-Soo Huh, and Duk-Dong Lee. "Fabrication and Characteristics of SnO2 Gas Sensor Array for Volatile Organic Compounds Recognition." Thin Solid Films 416, no. 1–2 (September 2, 2002): 271–78. doi:10.1016/S0040-6090(02)00619-3.

110 Srivastava, A.K., 2003. Detection of volatile organic compounds (VOCs) using SnO2 gas-sensor array and artificial neural network. Sensors and Actuators B: Chemical 96, 24–37. doi:10.1016/S0925-4005(03)00477-5

111 Zampolli, S., Elmi, I., Ahmed, F., Passini, M., Cardinali, G.C., Nicoletti, S., Dori, L., 2004. An electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring applications. Sensors and Actuators B: Chemical 101, 39–46. doi:10.1016/j.snb.2004.02.024

112 Penza, M., Cassano, G., Aversa, P., Antolini, F., Cusano, A., Consales, M., Giordano, M., Nicolais, L., 2005. Carbon nanotubes-coated multi-transducing sensors for VOCs detection. Sensors and Actuators B: Chemical, Eurosensors XVIII 2004 The 18th European Conference on Solid-State Transducers 111–112, 171–180. doi:10.1016/j.snb.2005.06.055

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An array of nanosized sensors (e-nose system with nanosensors) was applied to detect a mixture of organic gases [113]. The authors constructed nanostructured array elements consisting of thin film assemblies of alkanethiolate-monolayer-capped gold nanoparticles (2 nm), which were formed by molecularly mediated assembly using mediators or linkers of different chain lengths and functional groups. Each array element displayed linear response to the vapour concentration of benzene, toluene, xylenes, nitrobenzene, 2-nitrotoluene and 3-nitrotoluene. A set of artificial neural networks (ANNs) along with principle component analysis (PCA) technique was used for the analysis of the sensing response data for the VOCs. However, the tested concentration levels of organic chemicals ranged from several to thousands of µmol/mol, which are too high for the ambient air application.

In 2006, Wolfrum et al. [114] presented a sensors arrays based on 14 MOx Figaro TGS 2602 sensors with different power supply in the range 1 to 5 V plus a temperature and a humidity sensor. After laboratory calibration, Partial Least Square technique was used for data treatment and quantification of up to 10 VOCs in the range 10 to 300 nmol/mol adapted for indoor air monitoring.

In 2008, De Vito et al [115] presented an e-nose made of 7 low-cost metal oxide sensors manufactured by Pirelli Labs (IT). In this paper, the authors presented a field calibration method able to solve the lack of selectivity and stability of MOx using a neural calibration for the prediction of benzene concentrations using a gas multi-sensor device (solid-state) designed to monitor urban environment pollution. The feasibility of a sensor fusion algorithm as a calibrating tool for the multi-sensor device is discussed. A conventional air pollution monitoring station is used to provide reference data. Results are assessed by means of prediction error characterization throughout a 13 months long interval and discussed. Relationship between training length and performances are also investigated. A neural calibration obtained using a small number of measurement days revealed to be capable to limit the absolute prediction error for more than 6th months, after which seasonal influences on prediction capabilities at low-concentrations suggested the need for a further calibration.

3.7.3 Commercially available electronic Nose and sensor arrays

The µChemLab developed by Sandia National Laboratories does not seems to have application in the field of BTEX and VOC monitoring in ambient air [116]. It is however, an example of a hand-held miniaturized GC instrument for VOC measurement that incorporates a microfabricated etched column. It comprised a pre-concentrator consisting of a thin silicon nitride membrane supporting a patterned metal film-heating element, a 1 m long 100 × 400 µm high-aspect ratio GC column on a silicon wafer and an array of surface acoustic wave sensors.

Some examples of commercially available sensor arrays are the eNose of Comon-Invent consisting of 4 different semi-conductor sensors, the Aerekaprobe of The eNose Company using a system with 1 to 12 micro-hotplate temperature modulated metal-oxide sensors, and the Airsense PEN3 consisting of 10 different metal oxide single thick film sensors working at temperatures from 350 to 500 °C. The range of measurable gas concentrations of these sensor arrays varies from nmol/mol to upper µmol/mol.

4 Performance evaluation and validation studies

A little number of VOC sensor performance evaluations can be found in literature. An evaluation of the ppbRAE3000 is reported in the ISO/FDIS 16000-29:2014 [117], Indoor Air – part. 29: test methods for VOC detectors. The instrument was tested in an exposure chamber at 24 °C and 50 % of relative humidity. VOC mixtures were prepared by dilution of gas cylinders with zero air using Mass Flow Controllers delivering a total flow of 800 ml/min. Unfortunately, the VOC level of concentration were very high, generally several µmol/mol (toluene equivalent between 0.1 and 6 mg/m³), which correspond to the expected VOC levels in indoor air

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113 Han, Li, Xiajing Shi, Wendy Wu, F. Louis Kirk, Jin Luo, Lingyan Wang, Derrick Mott, et al. "Nanoparticle-Structured Sensing Array Materials and Pattern Recognition for VOC Detection." Sensors and Actuators B: Chemical, ISOEN 2003 - Selected Papers from the 10th International Symposium on Olfaction and Electronic Noses., 106, no. 1 (April 29, 2005): 431–41. doi:10.1016/j.snb.2004.09.003.

114 Wolfrum, Edward J., Robert M. Meglen, Darren Peterson, and Justin Sluiter. "Metal Oxide Sensor Arrays for the Detection, Differentiation, and Quantification of Volatile Organic Compounds at Sub-Parts-per-Million Concentration Levels." Sensors and Actuators B: Chemical 115, no. 1 (May 23, 2006): 322–29. doi:10.1016/j.snb.2005.09.026.

115 De Vito, S., Massera, E., Piga, M., Martinotto, L., Di Francia, G., 2008. On field calibration of an electronic nose for benzene estimation in an urban pollution monitoring scenario. Sensors and Actuators B: Chemical 129, 750–757. doi:10.1016/j.snb.2007.09.060

116 https://ip.sandia.gov/technology.do/techID=83

117 ISO/TC 146/SC6, ISO/FDIS 16000-29, Indoor Air – part. 29: test methods for VOC detectors, 2014-04-05

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studies. Reference values for the VOC mixtures were established by GC-MS. The responses of the ppbRAE3000, were given as to isobutylene equivalent without using the correction factor of each compound in the VOC mixtures (see in Appendix I: PID correction factors for various gases and lamp energies (9.6, 10.6 and 11.6 eV) calibrated to isobutylene). The difference of indications between the ppbRAE3000 and the GC-MS measurements for each VOC mixed gas (toluene, a mixture of two VOC and mixture of six VOC) were 27,9 %, −31,6 %, and 4,9 %, respectively. These tests are not adapted to the field of air quality monitoring both because of the level of concentration being tested and the lack of identification of the performance for each compound.

The United States Environmental Protection Agency (US-EPA) has published a report about the evaluation of VOC sensors [118]. This report summarizes the results of evaluations performed on low cost (<$2500) sensors. A total of five devices were incorporated into laboratory and field evaluation with one of those being an EPA developed device which used a commercially-available VOC photoionization detector (PID) as the sensing element. The laboratory evaluations involved testing the devices to a stepwise pattern of VOC concentrations at ambient levels (benzene < 25 nmol/mol) in an exposure chamber. The selected sensors consisted of the UniTec SENS-IT, AirBase CanarIT, CairPol CairClip, APPCD PID (PID sensor developed by US-EPA) and ToxiRAE Pro. It was shown during the lab experiments that the APPCD-PID and UniTec SENS-IT responses appeared well correlated with reference values of benzene and benzene/1,3-butadiene/tetrachloroethylene mixtures at concentrations well below 25 nmol/mol for benzene and 75 nmol/mol for the VOC mixtures. These results demonstrate the detection capabilities of the two sensors at these levels that would be useful for non-industrial environmental monitoring. However, issues with noisy response outputs were observed that limited the usability of some of the named devices. The author emphasized the need of improving some key features as ease of use, simplicity of operation, and ease of data recovery. They concluded that low cost VOC technologies appeared to be limited in both their capability and variety of technologies being employed. PID components still appears to be the prominent sensing element available. However, these come with inherent pros and cons (selectivity, drift over time …) which must be considered when trying to use such a device to estimate VOC concentrations under a variety of monitoring scenarios.

The devices were first evaluated for their response to a single VOC (benzene). If the device revealed some ability to detect benzene at even 25 nmol/mol it was then challenged with an atmosphere consisting of three VOCs (benzene, 1,3-butadiene, and tetrachloroethylene). These compounds were selected because of the availability of well qualified test gases and the fact they represented a variety of VOC moieties (structural variability). NGAM devices were deployed at an outdoor near road test platform for an extended period where wide variability of VOC conditions were expected to exist. The research plan involved direct comparison of the NGAM response to GC reference data from collocated measurements obtained at the test site. Reference data were ultimately not available for the intended comparisons (instrument malfunction and insufficient resources to conduct a timely repair). Therefore, field data provided here are limited to non-reference comparisons between NGAM devices. Such comparisons, providing a non-quantitative assessment of true VOC response still have the potential of yielding useful information on the relative response characteristics of the NGAM VOC devices evaluated.

5 Summary and Discussion

The first category reviewed consisted of the sensors from commercial Original Equipment Manufacturer. PID, MOx and amperometric sensors of OEM are either not enough selective (PID) or not enough sensitive (MOx or amperometric sensors) for measuring levels of nmol/mol to hundreds of pmol/mol's. Their limit of detection are 2 to 3 order of magnitude too high for monitoring benzene in ambient air at the 1 nmol/mol limit of detection. However, it may be worth to test the MOx of Unitec model Sens3000/SensIT for its claimed low limit of detection although the tests by US-EPA presented significant results at about 25 nmol/mol.

Portable Photo Ionization Detector instruments, in particular the ones including filtering or absorbing cartridges, may be an alternative at level from 10 nmol/mol for the ones selective to benzene (Tiger Select Benzene and UltraRAE3000). They are still about one order of magnitude too high as limit of detection.

The portable Gas Chromatographs and ion-mobility spectrometer would be both sensitive and selective. Unfortunately they are simply too expensive for the market of low-cost sensors. Portable GC/IMS also appear to be too expensive. However, in this category, we will investigate two prototypes, the miniaturized GC of

[118] *Ron Williams, Amanda Kaufman, Sam Garve, Next Generation Air Monitoring (NGAM) VOC Sensor Evaluation Report, Office of Research and Development, National Exposure Research Laboratory, EPA/600/R-15/122 | May 2015 | www.epa.gov/ord*

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Zampolli/CNR and the UV spectometer of Camou/NTT if they became commercially available since they seem to include miniaturised technology (MEMS) of lower cost.

Among research studies, we could find prototypes or semi-commercial systems including SiC-FET and multi MOx sensors operated in Temperature Operation Cycle that offer both nmol/mol or sub nmol/mol sensitivity with selectivity to specified VOCs. A few advanced prototypes of miniaturized Gas Chromatographs can be found in literature with equivalent or better sensitivity and selectivity.

Finally, multi sensors coupled with artificial neural network algorithms can be also considered a possible candidate sensor system (DeVito/ENEA).

In conclusion we advise to investigate the following sensors in order to select the final candidate for the following steps of the Key-VOCs sensors:

Manufacturer Institutes	Model	Principle	References
3s	Not available	MOS + TCO	The core system has been tested for selective pollutant identification in the low nmol/mol range, as reported in [Error! Bookmark not defined.]
Aeroqual	VM sensor with a resolution of 0.001 µmol/mol mounted on SM50 module	Semiconductor	Data sheet, see in appendix
Nano-Sense	Not available	Semiconductor	Use the same algorithm as 3S see [Error! Bookmark not defined.]
University of Linkoping	Not available	SiC-FET	See [Error! Bookmark not defined.]
Bentekk	X-PID	Portable GC + PID sensor	One Poster at PITTCON 2013 and personal communication, see http://www.bentekk.com/en/
CNR - IMM Bologna	miniGC	Portable GC + PID sensor	See [96, 97 and 98], sensors updated from MOx to PID
Ion Science	Tiger Select benzene	Portable hand held based on PID sensors	Data sheet, see in appendix
RAE	UltraRAE 3000 and ppbRAE 3000	Portable hand held based on PID sensors	Data sheet, see in appendix
ENEA	Not available	E-nose and artificial neural network	See [115]
NTT Microsystem Integration Laboratories	Not available	Potable UV absorption spectroscopy	See [83 and 84]
Mocon Baseline	item 045-014 (color Blue)	PID	Data sheet, see in appendix
Alphasense	PID-AH	PID	Data sheet, see in appendix

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6 Appendix I: PID correction factors for various gases and lamp energies (9.6, 10.6 and 11.6 eV) calibrated to isobutylene

Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Acetaldehyde	C_2H_4O			5.5	+			10.23
Acetic Acid	$C_2H_4O_2$	NR	+	22.0	+	2.6	+	10.66
Acetic Anhydride	$C_4H_6O_3$	NR	+	6.1	+	2.0	+	10.14
Acetone	C_3H_6O	1.2	+	1.1	+	1.4	+	9.71
Acetonitrile	C_2H_3N					100.0		12.19
Acetylene	C_2H_2					2.0		11.40
Acrolein	C_3H_4O	42.0	+	3.9	+	1.4	+	10.10
Acrylic Acid	$C_3H_4O_2$			12.0	+	2.0	+	10.60
Acrylonitrile	C_3H_3N			NR	+	1.2	+	10.91
Allyl alcohol	C_3H_6O			2.4	+	1.7		9.67
Allyl chloride	C_3H_5Cl			4.3		0.7		9.90
Ammonia	H_3N	NR	+	9.7	+	5.7	+	10.16
Amyl alcohol	$C_5H_{12}O$			5.0				10.00
Aniline	C_7H_7N	0.5	+	0.5	+	0.5	+	7.72
Anisole	C_7H_8O			0.8				8.21
Benzaldehyde	C_7H_6O					1.0		9.49
Benzene	C_6H_6	0.6	+	0.5	+	0.6	+	9.25
Benzonitrile	C_7H_5N			1.6				9.62
Benzyl chloride	C_7H_7Cl			2.0		0.7		
Bromobenzene	C_6H_5Br			0.6		0.5		8.98
Bromoform	$CHBr_3$	NR	+	2.5	+	0.5	+	10.48
1-Bromopropane	C_3H_7Br	150.0	+	1.5	+	0.6	+	10.18
Butadiene	C_4H_6			1.0	+	1.1		9.07
1,3-Butadiene diepoxide	$C_4H_6O_2$	25.0	+	3.5	+	1.2		~ 10
Butane	C_4H_{10}					1.2		10.53
1-Butanol	$C_4H_{10}O$	70.0	+	4.7	+	1.4	+	9.99
1-Butene	C_4H_8			0.9				9.58
2-Butoxyethanol	$C_6H_{14}O_2$	1.8	+	1.2	+	0.6	+	< 10
n-Butyl acetate	$C_6H_{12}O_2$			2.6	+			10
n-Butyl acrylate	$C_7H_{12}O_2$			1.6	+	0.6	+	
Butylamine	$C_4H_{11}N$			7				8.71
Butyl mercaptan	$C_4H_{10}S$			0.5				9.14
Carbon disulfide	CS_2			1.2	+	0.3		10.07
Carbon tetrachloride	CCl_4	NR	+	NR	+	1.7	+	11.47
Chlorine	Cl_2					1	+	11.48
2-Chloro-1,3-butadiene	C_4H_5Cl			3				
Chlorobenzene	C_6H_5Cl	0.44	+	0.4	+	0.39	+	9.06
1-Chloro-1,1-difluoroethane (R-142B)	$C_2H_3ClF_2$			NR		NR		12
Chlorodifluoromethane	$CHClF_2$	NR		NR		NR		12.2

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Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Chloroethane	C_2H_5Cl	NR	+	NR	+	1.1	+	10.97
Chloroethanol	C_2H_5ClO							10.52
2-Chloroethyl methyl ether	C_3H_7ClO			3				
Chloroform	$CHCl_3$	NR	+	NR	+	3.5	+	11.37
o-Chlorotoluene	C_7H_7Cl			0.5		0.6		8.83
p-Chlorotoluene	C_7H_7Cl					0.6		8.69
Crotonaldehyde	C_4H_6O	1.5	+	1.1	+	1	+	9.73
Cumene	C_9H_{12}	0.58	+	0.5	+	0.4	+	8.73
Cyanogen bromide	CNBr	NR		NR		NR		11.84
Cyanogen chloride	CNCl	NR		NR		NR		12.34
Cyclohexane	C_6H_{12}			1.4	+			9.86
Cyclohexanol	$C_6H_{12}O$					1.1		9.75
Cyclohexanone	$C_6H_{10}O$	1	+	0.9	+	0.7	+	9.14
Cyclohexene	C_6H_{10}			0.8	+			8.95
Cyclohexylamine	$C_6H_{13}N$			1.2				8.62
Cyclopentane	C_5H_{10}					0.6		10.51
Decane	$C_{10}H_{22}$	4	+	1.4	+	0.4	+	9.65
Diacetone alcohol	$C_6H_{12}O_2$			0.7				
1,2-Dibromoethane	$C_2H_4Br_2$	NR	+	1.7	+	0.6	+	10.37
o-Dichlorobenzene	$C_6H_4Cl_2$	0.54	+	0.47	+	0.38	+	9.08
Dichlorodifluoromethane	CCl_2F_2			NR	+	NR	+	11.75
1,1-Dichloroethane	$C_2H_4Cl_2$							11.06
1,2-Dichloroethane	$C_2H_4Cl_2$			NR	+	0.6	+	11.04
1,1-Dichloroethene	$C_2H_2Cl_2$			0.9				9.79
c-1,2-Dichloroethene	$C_2H_2Cl_2$			0.8				9.66
t-1,2-Dichloroethene	$C_2H_2Cl_2$			0.5	+	0.3	+	9.65
1,1-Dichloro-1-fluoroethane (R-141B)	$C_2H_3Cl_2F$	NR	+	NR	+	2	+	
1,2-Dichloropropane	$C_3H_6Cl_2$					0.7		10.87
2,3-Dichloro-1-propene	$C_3H_4Cl_2$	1.9	+	1.3	+	0.7	+	<10
2,2-Dichloro-1,1,1-trifluoroethane (R-123)	$C_2HCl_2F_3$	NR	+	NR	+	10.1	+	11.5
Diesel Fuel #1	m.w. 226			0.9	+			
Diesel Fuel #2	m.w. 216			0.7	+	0.4	+	
Diethylamine	$C_4H_{11}N$			1	+			8.01
3-Diethylaminopropylamine	$C_7H_{18}N_2$			1.3				
Diethylmaleate	$C_8H_{12}O_4$			4				
N,N-Dimethylacetamide	C_4H_9NO	0.87	+	0.8	+	0.8	+	8.81
Dimethylamine	C_2H_7N			1.5				8.23
Dimethyl disulfide	$C_2H_6S_2$	0.2	+	0.2	+	0.2	+	7.4
N,N-Dimethylformamide	C_3H_7NO			0.8				9.13
1,1-Dimethylhydrazine	$C_2H_8N_2$			0.8	+	0.8	+	7.28

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Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Dimethyl sulfate	$C_2H_6O_4S$	~23		~20	+	2.3	+	
1,4-Dioxane	$C_4H_8O_2$			1.1				9.19
Epichlorohydrin	C_2H_5ClO	~200	+	8.5	+	1.4	+	10.2
Ethane	C_2H_6			NR	+	15	+	11.52
Ethanol	C_2H_6O			12	+	8		10.47
Ethanolamine (Not Recommended)	C_2H_7NO			~4	+	~3	+	8.96
Ethene	C_2H_4			10	+	3		10.51
2-Ethoxyethanol	$C_4H_{10}O_2$			3.5				9.6
Ethyl acetate	$C_4H_8O_2$			4.6	+			10.01
Ethyl acrylate	$C_5H_8O_2$			2.4	+	1	+	(<10.3)
Ethylamine	C_2H_7N			0.8				8.86
Ethylbenzene	C_8H_{10}	0.52	+	0.5	+	0.5	+	8.77
Ethylene glycol	$C_2H_6O_2$			16	+	6	+	10.16
Ethylene oxide	C_2H_4O			19	+	3	+	10.57
Ethyl ether	$C_4H_{10}O$			1.1	+			9.51
Ethyl formate	$C_3H_6O_2$					1.9		10.61
2-Ethyl hexyl acrylate	$C_{11}H_{20}O_2$			1.1	+	0.5	+	
Ethyl (S)-(-)-lactate	$C_5H_{10}O_3$	13	+	3.2	+	1.6	+	~10
Ethyl mercaptan	C_2H_6S			0.6				9.29
Ethyl sulfide	$C_4H_{10}S$			0.5	+			8.43
Formaldehyde	CH_2O					0.6		10.87
Furfural	$C_5H_4O_2$			0.9	+	0.8	+	9.21
Gasoline #1	m.w. 72			0.9	+			
Gasoline #2, 92 octane	m.w. 93	1.3	+	1	+	0.5	+	
Glutaraldehyde	$C_5H_8O_2$	1.1	+	0.8	+	0.6	+	
Halothane	$C_2HBrClF_3$					0.6		11
HCFC-123 (see 2,2-Dichloro-1,1,1-trifluoroethane, R-123)								
HCFC-141B (see 1,1-Dichloro-1-fluoroethane)								
HCFC-142B (see 1-Chloro-1,1-difluoroethane)								
n-Heptane	C_7H_{16}			2.6	+	0.5		9.92
1,1, 1,3,3,3-Hexamethyldisilazane, HMDS	$C_6H_{19}NSi_2$			0.2	+	0.2	+	~8.6
n-Hexane	C_6H_{14}	300		4.3	+	0.5	+	10.13
1-Hexene	C6H12	0.8		9.44				
Hydrazine	H_4N_2			2.6	+	2.1	+	8.1
Hydrogen	H_2	NR	+	NR	+	NR	+	15.43
Hydrogen peroxide	H_2O_2	NR	+	NR	+	NR	+	10.54
Hydrogen sulfide	H_2S	NR	+	3.3	+	1.5	+	10.45
Iodine	I_2	0.1	+	0.1	+	0.1	+	9.4
Isobutane	C_4H_{10}			100	+	1.2	+	10.57
Isobutanol	$C_4H_{10}O$	19	+	3.8	+	1.5		10.02

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Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Isobutene	C_4H_8	1	+	1	+	1	+	9.24
Isobutyl acrylate	$C_7H_{12}O_2$			1.5	+	0.6	+	
Isoflurane	$C_3H_2ClF_5O$							
Isooctane	C_8H_{18}			1.4				9.86
Isopar G Solvent	m.w. 148			0.8	+			
Isopar M Solvent	m.w. 191			0.7	+	0.4	+	
Isophorone	$C_9H_{14}O$					3		9.07
Isoprene	C_5H_8	0.69	+	0.6	+	0.6	+	8.85
Isopropanol	C_3H_8O	500	+	6	+	2.7		10.12
Isopropyl acetate	$C_5H_{10}O_2$			2.5				9.99
Isopropyl ether	$C_6H_{14}O$			0.8				9.2
Jet fuel JP-4	m.w. 115			1	+	0.4	+	
Jet fuel JP-5	m.w. 167			0.6	+	0.5	+	
Jet fuel JP-8	m.w. 165			0.6	+	0.3	+	
Kerosene (C10-C16 petro.distillate - see Jet Fuels)								
Mesitylene	C_9H_{12}	0.36	+	0.35	+	0.3	+	8.41
Methane	CH_4	NR	+	NR	+	NR	+	12.51
Methanol	CH_4O	NR	+	NR	+	2.5	+	10.85
2-Methoxyethanol	$C_3H_8O_2$	4.8	+	2.4	+	1.4	+	10.1
2-Methoxyethoxyethanol	$C_7H_{16}O_3$	2.3	+	1.2	+	0.9	+	<10
Methyl acetate	$C_3H_6O_2$					1.6		10.27
Methyl acrylate	$C_4H_6O_2$			3.7	+	1.2	+	-9.9
Methylamine	CH_5N			1				8.97
Methyl bromide	CH_3Br	110	+	1.7	+	1.3	+	10.54
Methyl t-butyl ether	$C_5H_{12}O$			0.9	+			9.24
Methyl cellosolve (see 2-Methoxyethanol)								
Methyl chloride	CH_3Cl	NR	+	NR	+	0.7	+	11.22
Methylcyclohexane	C_7H_{14}			1.1				9.64
Methylene chloride	CH_2Cl_2	NR	+	NR	+	0.89	+	11.32
Methyl ethyl ketone	C_4H_8O	0.86	+	0.9	+	1.1	+	9.51
Methylhydrazine	$C_2H_6N_2$	1.4	+	1.2	+	1.3	+	7.7
Methyl isobutyl ketone	$C_6H_{12}O$			1.2	+	0.9		9.3
Methyl isocyanate	C_2H_3NO	NR	+	4.6	+	1.5		10.67
Methyl mercaptan	CH_4S			0.6				9.44
Methyl methacrylate	$C_5H_8O_2$			1.4	+	1.4		9.7
Methyl propyl ketone	$C_5H_{12}O$			0.9	+	0.8	+	9.38
N-Methyl-2-pyrrolidinone	C_5H_9NO	1	+	0.8	+	0.9	+	9.17
Methyl salicylate	$C_8H_8O_3$			2				
a-Methylstyrene	C_9H_{10}			0.5				8.18
Mineral spirits (Stoddard Solvent, see also Viscor 120B)				0.7	+	0.39	+	

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Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Mineral Spirits Viscor 120B Calibration Fluid		1	+	0.7	+	0.3	+	
Naphthalene (Mothballs)	$C_{10}H_8$	0.45	+	0.4	+	0.4	+	8.13
Nitric oxide	NO			5.2	+	2.8	+	9.26
Nitrobenzene	$C_6H_5NO_2$	2.6	+	1.9	+	1.6	+	9.81
Nitroethane	$C_2H_5NO_2$					3		10.88
Nitrogen dioxide	NO_2			NR	+	NR	+	9.75
Nitromethane	CH_3NO_2					4		11.02
2-Nitropropane	$C_3H_7NO_2$					2.6		10.71
Nonane	C_9H_{20}			2				9.72
n-Octane	C_8H_{18}	13.2	+	1.8	+			9.82
Pentane	C_5H_{12}	80	+	8.4	+	0.7	+	10.35
Peracetic acid	$C_2H_4O_3$	NR	+	NR	+	2.3	+	
Peracetic/Acetic acid mix	$C_2H_4O_3/C_2H_4O_4$			50	+	2.5	+	
Perchloroethene	C_2Cl_4	0.69	+	0.57	+	0.31	+	9.32
PGME	$C_6H_{12}O_3$	2.4	+	1.5	+	1.1	+	
PGMEA	$C_6H_{12}O_3$	1.65	+	1	+	0.8	+	
Phenol	C_6H_6O	1	+	1	+	0.9	+	8.51
Phosphine in N2	PH_3			2	+	1.4		9.87
Photocopier Toner				0.5	+	0.3	+	
3-Picoline	C_6H_7N			0.9				9.04
a-Pinene	$C_{10}H_{16}$			0.3	+	0.5		8.07
b-Pinene	$C_{10}H_{16}$	0.38	+	0.4	+	0.4	+	~8
Piperylene, isomer mix	C_5H_8	0.76	+	0.7	+	0.6	+	8.6
Propane	C_3H_8			NR	+	1.8	+	10.95
n-Propanol	C_3H_8O			6		1.7		10.22
Propene	C_3H_6			1.7	+			9.73
Propionaldehyde	C_3H_6O			1.9				9.95
n-Propyl acetate	$C_5H_{10}O_2$			3.5				10.04
Propylene oxide	C_3H_6O			6.5		2		10.22
Propyleneimine	C_3H_7N	1.5	+	1.3	+	1	+	9
Pyridine	C_5H_5N	0.78	+	0.7	+	0.7	+	9.25
RR7300 (70:30 PGME/PGMEA)	$C_4H_{10}O_2$/ $C_6H_{12}O_3$	1.4	+	1	+			
Stoddard Solvent - see Mineral Spirits								
Styrene	C_8H_8	0.45	+	0.4	+	0.4	+	8.43
Sulfur dioxide	SO_2			NR	+	NR	+	12.32
1,1,1,2-Tetrachloroethane	$C_2H_2Cl_4$					1.3		~11.1
1,1,2,2-Tetrachloroethane	$C_2H_2Cl_4$	NR	+	NR	+	0.6	+	~11.1
Tetraethyllead	$C_8H_{20}Pb$	0.4		0.3		0.2		~11.1
Tetraethyl orthosilicate	$C_8H_{20}O_4Si$			0.7	+	0.2	+	~9.8
1,1,1,2-Tetrafluoroethane	$C_2H_2F_4$			NR		NR		
Tetrafluoromethane	CF_4			NR	+	NR	+	>15.3

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Compound Name	Formula	9.8	C	10.6	C	11.7	C	IP (eV)
Tetrahydrofuran	C_4H_8O	1.9	+	1.7	+	1	+	9.41
Therminol		0.9	+	0.7	+			
Toluene	C_7H_8	0.54	+	0.5	+	0.51	+	8.82
Tolylene-2,4-diisocyanate	$C_9H_6N_2O_2$	1.4	+	1.4	+	2	+	
1,1,1-Trichloroethane	$C_2H_3Cl_3$			NR	+	1	+	11
1,1,2-Trichloroethane	$C_2H_3Cl_3$	NR	+	NR	+	0.9	+	11
Trichloroethene	C_2HCl_3	0.62	+	0.5	+	0.4	+	9.47
1,1,2-Trichlorotrifluoroethane CFC-113	$C_2Cl_3F_3$			NR		NR		11.99
Triethylamine	$C_6H_{15}N$			1.3				7.5
1,1,2-Trifluoroethane	$C_2H_3F_3$					34		12.9
Trimethylamine	C_3H_9N			0.9				7.82
1,3,5-Trimethylbenzene (see Mesitylene)								
Turpentine	$C_{10}H_{16}$			0.4				
Undecane	$C_{11}H_{24}$			2.0				9.56
Vinyl actetate	$C_4H_6O_2$			1.2				9.19
Vinyl bromide	C_2H_3Br			0.4				9.80
Vinyl chloride in N2	C_2H_3Cl			2.0	+	0.6	+	9.99
1-Vinyl-2-pyrrolidinone	C_6H_9NO	1.0	+	0.8	+	0.9	+	
Viscor 120B - see Mineral Spirits - Viscor 120B Calibration Fluid								
m-Xylene	C_8H_{10}	0.5	+	0.4	+	0.4	+	8.56
o-Xylene	C_8H_{10}	0.6	+	0.6	+	0.7		8.56
p-Xylene	C_8H_{10}			0.5	+	0.6	+	8.44

1. The values indicated by a plus (+) sign in the “C” column are confirmed values; all others are preliminary and subject to change.

2. The correction factors in this table were measured in dry air. Actual readings may vary with age and cleanliness of the lamp, relative humidity, components in the sample, and other factors. For accurate work, the instrument should be calibrated regularly under the operational conditions in which the instrument is used.

3. IP (eV) data was taken from the CRC Handbook of Chemistry and Physics, 73rd Edition, and NIST Standard Ref. Database 19A.

(The tables with energies and IP were taken from Hazardous Gas Monitors, A Practical Guide to Selection, Operation and Applications, by Jack Chou --President & Founder, International Sensor Technology, Publication: October, 1999, ISBN: 0-07-135876-5, http://intlsensor.com/pdf/PIDcorrectionfactors.pdf)

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7 Appendix II: Performance indicators of commercially available sensors extracted from sensors' data sheet

List of sensor's technical information:

If possible please give a reference for each information given explaining where you got them.

1- Short description of the sensor including:

- commercial availability
- manufacturer and supplier
- sensor model
- method of preparation of sensor
- principle of operation (electrochemical, number of electrode, MOx…)
- data treatment and/or data processing (e.g. zero correction, determination of level of gaseous concentration, interference corrections, zero or span drift)
- suggested calibration method

2- Metrological characteristics (performances):

- sensitivity: known or estimated range of concentration, response time, limit of detection (3s)/quantification (10s), linearity, hysteresis...
- stability: short and long drift (at Zero and span value), lifetime
- selectivity: qualitative or quantitative effect of chemical interfering compounds and physical interferences (temperature, humidity pressure, wind velocity)

3- Supplementary equipment:

- power supply
- power consumption
- heater (if used): power consumption, temperature (constant or cycling) for MOx
- test board (if used)
- output, data acquisition

4- Any other information:

- operating conditions (temperature, humidity and pressure range)
- manufacturer suggested applications: ambient air monitoring, indoor air monitoring, monitoring of population exposure, emission monitoring
- availability of evaluation of sensor: laboratory tests, field tests and estimation of uncertainty of measurement using the micro-sensor
- details of the protection box and/or sensor holder used with the material used for construction
- references of datasheet (web page, file to be added as an annex…)

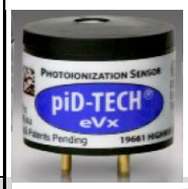
8 Appendix III: Review of sensor specifications and data sheets

The information in the following tables is given for the convenience of users and does not constitute an endorsement by the authors nor the institutions to which they are affiliated for any of these products. The table hereafter is filled with data specified by manufacturers, and is not estimated in a uniform way by different manufacturers. This can result in inhomogeneity of criteria and sensor performances that cannot be compared. We did our best to check the given information but errors in the tabulated values cannot be excluded. The selection of equipment is a result of our analysis of the market of VOC sensors. However we cannot excluded that we missed other suitable instruments.

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	ppb MiniPiD white (10.6 eV UV lamp)	Commercialy available, OEM markets	Ion Science Messtechnik GMBH, Laubach 30, Metmann-Neandertal-40822, GERMANY, Tel: +49 2104 14480, Fax: +49 2104 144825, info@ism-d.de, Web: www.ism-d.de	PID Sensors, UV lamp energy: 10.6 eV	No data	Linear: +1% at < 50 ppm	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	IBE: 25 mV/ppm
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	piD-TECH eVx Blue 045-014, (10.6 eV UV lamp)	Commercialy available, OEM markets	Europe, Middle East, Africa & Russia Sales Manager, Michael Buckley, Phone: 508.209.8533, Email:michael.buckley@baselineindustries.com	PID Sensors, UV lamp energy: 10.6eV and 10.0eV lamp energies available	No data	No data, likely linear as for PID detector	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	IBE: 1.228 V/ppm (0.045-2.5 V for 2 ppm)
	piD-TECH plus, 043-235	Commercialy available, OEM markets		PID Sensors, UV lamp energy: 10.6eV, 10.0eV, and 9.6eV lamp energies available	No data	No data, likely linear as for PID detector	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	IBE: 0.123 V/ppm (0.045-2.5 V for 20 ppm)
AlphaSense LTD, Sensor Technology House 300 Avenue West Skyline 120 Great Notley Essex CM77 7AA United Kingdom Tel: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 Email: sensors@alphasense.com	PID-AH for VOCs- (10.6 eV UV lamp), The PID-A1 exists but for higher range of concentration (0-6000 ppm)	Commercialy available, OEM markets		PID Sensors, IP < 10.6 eV	No data	No data, likely linear as for PID detector at least up to 10 ppm	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	IBE: >20 mV/ppm
Dräger Safety France SAS 3c route de la Fédération, BP 80141 67025 Strasbourg Cedex 1 Tel +33 3 88 40 59 29 Fax +33 3 88 40 76 67	Multi-PID 2	Portable instrument, commercialy available		Portable hand held instrument using a PID sensor, UV lamp 10.6 eV	2 and 3 point calibration	No data, zero air and span should be used according to the user manual	No data	No data	No data	The sensor mounts a PID pre-filter tube for benzene which adsorbs all substances with the exception of benzene to selectively measure benzene	No data

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	IBE: 1 ppb - 40 ppm	<3s, 2 s with flow velocity < 1 m/s and flow rate > 3 mL/s	IBE: 1 ppb, benzene: 0.5 ppb	No data	No data	1 % at < 50 ppm	No data	No data	No data	> 5 years, except lamp and detector, warranty: 12 months from date of shipment	VOC's with ionisation potentials < 10.6 eV	No data	Temperature and humidity	Quantitative effect, see user manual
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	IBE: 0.5 ppb - 2 ppm	No data	IBE: 0.5 ppb -> Benzene: 0.25 ppb	No data	No data	No data	No data	No data	No data	No data	VOC's with ionisation potentials < 10.6 eV	No data	No data	No data
	IBE: 0-20 ppm, with the 10.6 EV UV lamp	< 5 s	IBE: 5 ppb -> Benzene: 2.5 ppb	No data	No data	No data	No data	No data	No data	Waranty: 6000 hours, 18 months from shipment or 12 months from installation	VOC's with ionisation potentials < UV energy of the chosen lamp	No data	No data	No data
AlphaSense LTD, Sensor Technology House 300 Avenue West Skyline 120 Great Notley Essex CM77 7AA United Kingdom Tel: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 Email: sensors@alphasense.com	IBE: 5 ppb - 50 ppm	< 3 s	IBE: 1 ppb (benzene: 0.5 ppb)	No data	No data	3% between 10 and 50 ppm IBE	No data	No data	n.a	5 years, electronic 24 months years, lamps excluded (6000 hrs)	PID are sensitive to all VOCs with ionisation potential lower to lamp energy	No data	No data	No data
Dräger Safety France SAS 3c route de la Fédération, BP 80141 67025 Strasbourg Cedex 1 Tel +33 3 88 40 59 29 Fax +33 3 88 40 76 67	Benzene: 0.05 - 1000 ppm	< 3 s	Benzene: 50 ppb	No data	Repeatability: 1 % of calibration; accuracy for benzene: max(± 10 %, ± 1 ppm)	± 1 % at < 50 ppm	No data	No data	No data	> 5 years (unlikely that the lamp can last for 5 years)	VOCs, but not quantified by manufacturer	No data	No data	No data

Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	3 to 3.6 V or 3.6 to 10 V	110 mW at 3.3 V (150 ms 300 mW transient upon switch on)	No heater, krypton lamp (10.6 eV)	Not relevant	Not relevant	0.05 V to rail voltage	Operation: -40 - 60 °C, storage: -40 - 70 °C, effect of temp.: ± 10 % between -20 and 60 °C, vs 20 °C response	Operation: 0 - 99 % (not condensing), effect of humidity: - 10 % from 0 to 100 % (interaction with temperature)	No Data	9g	MiniPID is widely used across a number of industries and applications, including: personnel safety, industrial hygiene, site soil and air sampling, fugitive emissions and volatile spills, law enforcement, emergency response
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	3.2 to 5.5 V, 24 to 36 mA	80 to 200 mW	No data	No data	Contact manufactuer	0.045 - 2.5 V	Operation -20 to 60 °C, negligible effect between -40 and 60 °C	Operation from 0 to 90 %, Response: < 1 % @ 90 % RH, quenching: < 15 % @ 90 % RH	No data	8 g	Industrial Hygiene & Safety Monitoring, Confined Space Entry, Soil Contamination and Remediation, Hazmat Sites & Spills, Low Concentration Leak Detection, Indoor Air Quality, EPA Method 21
	3.2 to 10 V, current 20 - 30 mA	60 to 300 mW	No data	No data	Contact manufactuer	0.045 - 2.5 V	Operation: -20 to 40 °C	Operation: from 0 to 90 % non condensing, Effect: < 0.2 ppm @ 90 % RH, quenching effect: < 15 % @ 90 % RH	No data	8 g	This sensor can be utilized in an incredible variety of environmental and safety applications for industrial, commercial, and residential markets
AlphaSense LTD, Sensor Technology House 300 Avenue West Skyline 120 Great Notley Essex CM77 7AA United Kingdom Tel: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 Email: sensors@alphasense.com	3.3 V (3 to 3.6 V, regulated ± 0.01 mV)	110mW (1W at switch on during 200 ms)	none	none	Contact manufactuer	Direct voltage in mV range	From -40 to 55 °C. Effect: between 0 and 40 °C, output between 90 to 100 % of signal at 20 °C. At -20 °C, ouput at 140 % of signal at 20 °C.	0 to 95 % rel. Hum. Non condensing. Effect between 0 an 75 % re. Humidity near to zero.	No data	< 8 g	No data
Dräger Safety France SAS 3c route de la Fédération, BP 80141 67025 Strasbourg Cedex 1 Tel +33 3 88 40 59 29 Fax +33 3 88 40 76 67	100-240 VAC, 50-60 Hz; battery 12 VDC NiMH rechargeable cell, charing time 4/5 hrs	12 VDC, 1.0 A	No heater, krypton lamp (10.6 eV)	Not relevant	Not relevant	Logger with 15000 measurements, RS 232 to connect a PC	0 to 50 °C	0 to 95% relative humidity (non-condensing)	No data	860 g	Indoor air quality assessment, Soil contamination and land remediation, Industrial hygiene and safety monitoring, Arson investigation, Low-level VOC leak detection, Environmental emissions monitoring, Confined space entry, Atmosphere monitoring, First response to HazMat incidents

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	Temperature and humidity effect found in the user manual	No data	Data sheet and user manual	
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	Evaluation of temperature and humidity effect on the data sheet	No data	Data sheet	
	No data	No data	Data sheet	
AlphaSense LTD, Sensor Technology House 300 Avenue West Skyline 120 Great Notley Essex CM77 7AA United Kingdom Tel: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 Email: sensors@alphasense.com	Evaluation of temperature and humidity effect on the data sheet	No data	Data sheet	
Dräger Safety France SAS 3c route de la Fédération, BP 80141 67025 Strasbourg Cedex 1 Tel +33 3 88 40 59 29 Fax +33 3 88 40 76 67	No data	Not relevant, hand-held instrument	User manual	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
PID Analyzers, 2 Washington Circle, Unit 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=102plus	Model 102+	Portable instrument, commercialy available		Portable hand held instrument using a PID sensor, UV lamp: 9.5 or 10.62 or 11.7 eV. Fast response time, extended range, elimination of any moisture sensitivity, capability of having up to 4 sensors plus a ppb range, and pump & datalogging	Two point calibration for the PID uses a zero and a span gas. The time to calibrate is about 10 seconds.	No data. Since two points are used, a linear model can be assumed	No data	<2% over 24 hours	electronic zero (no zero gas needed	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	No data
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	VOC-Traq (Part #042-963)	Portable instrument, commercialy available	Zamax GmbH, Jahnstraße 6, D - 82216 Maisach / Germany, Tel + 49 8141 305083, Fax +49 8141 305084, martin.zach@zamax.de, www.zamax.de	Portable hand held sensor using a PID sensor Baseline-MOCON piD-TECH plus for Total Organic Volatile Compounds (TVOC)	No data	No data	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	No data
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	Club Personal PID Monitor	Portable instrument, commercialy available	Ion Science Messtechnik GMBH, Laubach 30, Metmann-Neandertal-40822, GERMANY, Tel: +49 2104 14480, Fax: +49 2104 144825, info@ism-d.de, Web: www.ism-d.de	Portable hand held sensor using a PID sensor, UV lamp 10 and 10.6 eV available	2 point calibration via docking station	No data, zero and span gases should be used according to the user manual	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	No data
	Tiger Select for benzene and total aromatic compound	Portable instrument, commercialy available		Portable hand held sensor using a PID sensor, Kr PID lamp with 10.0 eV filter pellet (10.6 eV lamp + an additional 10.0 eV glass filter is fitted in to the electrode stack)	2 to 3 point calibration via calibration kit	No data, zero and 1 or 2 span gases should be used according to the user manual	No data, Likely linear as for PIS sensors	No data	No data	The PID Select may be used in Total Aromatic Compound mode or including filter tube that only allows benzene to pass through. It also uses a 10 eV filter pellet to exclude IP > 10 eV	No data
Graywolf, SenSinG SolutionS, 6 research Drive (worldwide Headquarters), Shelton, Ct 06484 USA, Ph. (1)203-402-0477, 800-218-7997, fax:(1)203-402-0478, Salesteam@GraywolfSensing.com, www.GraywolfSensing.com	AdvancedSense DirectSens IAQ (TG502 or IAQ-610), PID (VOCs) Low Range	Portable instrument, commercialy available	Graywolf, SenSinG SolutionS, annacotty industrial Park, unit 1C , annacotty, County limerick , Ireland , Ph. (353) 61358044, fax: (353) 61358160	Portable hand held sensor using a PID sensor, UV lamp 10.6 eV	No data on method, calibration frequency: < 2 weeks by user and 12 months factory	No data, zero air and span should be used in the user manual	<10 ppb /day	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	No data

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
PID Analyzers, 2 Washington Circle, Unit 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=102plus	IBE: 0.001-20 with PID+ sensor	<1 s (t90)	IBE: ppb range with the optional PID + sensor	No data	+/- 1% of reading	No data. Accuracy: 97-98 % at 10 ppm	No data	<2% over 24 hours	No data	No data	VOCs, but not quantified by manufacturer	No data	No data	No data
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	IBE: 0.01 - 20 ppm -> benzene: 0.005 - 10 ppm	10 s (t90)	Benzene: 5 ppb	No data	No data	Accuracy: +/- 3% of reading, w/ constant temperature and pressure	No data	No data	No data	No data	VOC's with ionisation potentials < 10.6 eV	No data	No data	No data
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	IBE: 1 ppb -5000 ppm	13 s (T90)	IBE: 1 ppb; likely 0.5 ppb of benzene (resolution 1 ppb)	No data	No data	Linearity and Accuracy : ± 5 % display reading ± one digit benzene	No data	No data	No data	> 5 years	VOC's with ionisation potentials < 10.6 eV	No data	No data	No data
	Benzene: 10 ppb - 40 ppm	120 s	Benzene: 10 ppb, resolution 1 ppb	No data	No data	Linearity ± 5% to 40 ppm benzene, Accuracy: ± 10 % display reading ± one digit benzene	No data	No data	No data	> 5 years	Total aromatic compounds or benznene using a filter tube	No data	No data	No data
Graywolf, SenSinG SolutionS, 6 research Drive (worldwide Headquarters), Shelton, Ct 06484 USA, Ph. (1)203-402-0477, 800-218-7997, fax:(1)203-402-0478, Salesteam@GraywolfSensing.com, www.GraywolfSensing.com	VOCs (IBE): 0 to 20 ppm	<605s	Vocs (IBE): 5ppb (resolution 1 ppb), likely 2.5 ppb for benzene	No data	No data	No data	No data	No data, calibration every 2 weeks	<10 ppb /day (zero drift)	> 5 years except lamp & detector)	VOC's with ionisation potentials < 10.6 eV	No data	No data	No data

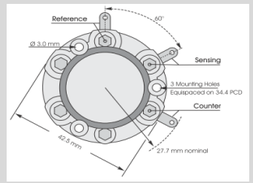
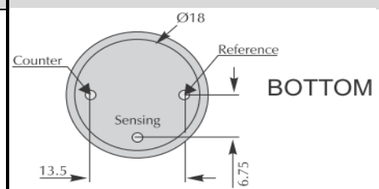
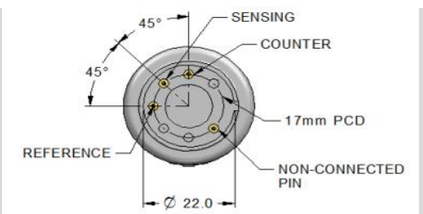
Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
PID Analyzers, 2 Washington Circle, Unit 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=102plus	Battery: nickel methal hydride rechargeable, Battery life- 8-10 hours	< 1 W	No heater, PID lamp	Not relevant	Not relevant	Manual or automatic datalogging (7,000 points) is available. The 102 has a built in real time clock. Viewer software (Windows 98-XP compatible) comes with the 102. RS232 output , 0-1 VSC output-programmable	No data	No data	No data	about 1 kg	Non-specific- Responds to VOC's & inorganic species (NH3, H2S, PH3, AsH3, etc.). Indoor Air Quality, Confined Space, Leak Detection, Wastewater, Chemical Plant, Pulp & Paper, Combustion leaks. Testing gas masks, residual gases in cylinders. Emergency response- spills from trucks & trains. First responders. Fugitive emissions. Storage Tanks . Building security
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	Rechargeable 50 hour battery for data logging without a PC, Powered from USB (5.0 VDC, 40 mA) or power supply	No data	No heater, krypton lamp (10.6 eV)	Not relevant	PC with USB or wireless USB extender	VOC-TRAQ PC software + USB cable	Operation from -20 to 40 °C	Operation from 0 to 90 % RH (non condensing)	No data	54 g	Air Quality Analysis For: Cleanrooms, Educational Facilities, Work Environments, Public Places, Leak Detection
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	Battery life 16 hrs, battery charge 4 hours		No heater, krypton lamp (10.6 eV)	Not relevant	Not relevant	USB 2.0, internal data logger. Docking Station OPTIONS: Charge only, Charge and USB communication, Charge, USB communication and calibration	Operation from -20 to 55 °C, storage: -25 to 60 °C	The patented Fence Electrode Technology minimises the effects of moisture and contamination, avoiding the need for humidity	No data		Industrial hygiene, Chemical and petrochemical plants, Oil & gas, Health & safety, Hazardous materials, Environmental, Aviation Maintenance, Agricultural gas production, Chemical Storage, Environmental Clean Up After Spillage, Filling Station Monitoring / Leakages, Fuel Vapour Detection, Fugitive Emissions, Fumigation Gases (such as formaldehyde), General Atmosphere Monitoring for Tracing Chemicals, General indoor air quality monitoring, Head Space Monitoring, Health & Safety, STEL & TWA Monitoring in Confined Spaces, Illegal Dumping of Chemicals, Indoor Air Quality Measuring Industrial Volatiles, Petrochemical Storage, Refinery environmental benzene, Screening Tool for First Responders, Sileage silos, Spillage Investigation, VOC Leak Detection, VOC Monitoring
	Li-ion: battery life 30 hrs, battery charge 6.5 hours, Alkaline: 3 x AA, 12 hrs life		No heater, UV lamp	Not relevant	Not relevant	USB 1.1, internal data logger	Operation from -20 to 60 °C, storage: -25 to 60 °C	Operation from 0 to 99 % (not condensing)			Total Aromatic Compounds (TAC) detection at loading docks and barge operations, Confined space entry pre-screening during refinery and plant maintenance screening during refinery and plant maintenance, Refinery down-stream monitoring, Hazardous material response, Marine spill response, GIS Leakage, Plant vessel inspection, Refinery environmental benzene
Graywolf, SenSinG SolutionS, 6 research Drive (worldwide Headquarters), Shelton, Ct 06484 USA, Ph. (1)203-402-0477, 800-218-7997, fax:(1)203-402-0478, Salesteam@GraywolfSensing.com, www.GraywolfSensing.com	2 x D cells; typical battery life 120 hrs	No data	No heater, krypton lamp (10.6 eV)	Not relevant	Not relevant	On windows tablet	Operation from -15 to 60 °C	Operation from 0 to 90 % (not condensing)	No data		Indoor air quality assessment

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
PID Analyzers, 2 Washington Circle, Unit 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=102plus	No data	Not relevant, hand-held instrument	http://www.hnu.com/products.php?v=102plus	
Baseline, a Mocon company, P.O. Box 649, 19661 Highway 36, Lyons, CO 80540, Tel: 1.800.321.4665, 1.303.823.6661, Fax: 303.823.5151, Web: www.baseline-mocon.com, Email: info@baselineindustries.com	No data	Not relevant, hand-held instrument	Data sheet	
Ion Science Ltd, The Way, Fowlmere, , Cambs, SG8 7UJ, UK, T: +44 (0) 1763 208 503, info@ionscience.com, www.ionscience.com	No data	Not relevant, hand-held instrument	Data sheet, user manual and http://www.ionscience.com/products/cub	
	No data	Not relevant, hand-held instrument	http://www.ionscience.com/products/tiger-select-benzene-and-total-aromatic-compound-detector	 
Graywolf, SenSinG SolutionS, 6 research Drive (worldwide Headquarters), Shelton, Ct 06484 USA, Ph. (1)203-402-0477, 800-218-7997, fax:(1)203-402-0478, Salesteam@GraywolfSensing.com, www.GraywolfSensing.com	No data	Not relevant, hand-held instrument	Data sheet	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
RAE Systems Inc., 3775, North First Street, San Jose, CA 95134 USA, raesales@raesystems.com	UltraRAE 3000	Portable instrument, commercialy available	RAE Systems UK Ltd D5 Culham Innovation Centre, Culham Science Centre, Abingdon, Oxon OX14 3DB, United Kingdom, Phone: +44 1865408368, Fax: +44 1235531119, Mobile: +44 7841362693, Email: aeuk@raeeurope.com	Portable hand held sensor using a PID sensor, Photoionization sensor with standard 9.8 eV or optional 10.6 eV or 11.7 eV lamps	2-point or 3-point calibration for zero and span. Calibration memory for 8 calibration gases, alarm limits, span values and calibration dates	No data, zero and 1 or 2 span gases should be used according to the user manual	No data	No data	No data	The sensor is selective thanks to a 9.8eV UV lamp and RAE-Sep™ benzene tube	No data
	ppbRAE 3000	Portable instrument, commercialy available		Portable hand held sensor using a PID sensor, Photoionization sensor with 9.8, 10.6, or 11.7 eV UV lamp	2-point calibration for zero and span. Calibration memory for 8 calibration gases, alarm limits, span values and calibration dates	No data, zero and span gases should be used according to the user manual	No data	No data	No data	PID are sensitive to VOCs gaseous interfering compounds. No correction is suggested by the manufacturer.	No data
City Technology Ltd, City Technology Centre, Walton Rd, Portsmouth PO6 1SZ, UK, Tel:+44 23 9232 5511, Fax:+44 23 9238 6611, www.citytech.com	3ETO CiTiceL	Commercialy available, OEM markets		3-electrode electrochemical cell, amperometric type, designed for Ethylene oxide	No Data	No Data	Maximum zero shift in pure air: 2 ppm equivalent. Typical baseline range in pure air: 0 to 1 ppm equivalent	< 5 % / year	No data	(CO), hydrocarbons (HC), and VOCs (see data sheet)	2.75 ± 0.5 µA/ppm
	4ETO CiTiceL	Commercialy available, OEM markets		3-electrode electrochemical cell, amperometric type, designed for Ethylene oxide	No Data	No Data	Maximum zero shift in pure air: 4 ppm equivalent. Typical baseline range in pure air: 0 to 3 ppm equivalent	< 5 % / year	No data	(VOC)	1.9 ± 0.5 µA/ppm
	7ETO CiTiceL	Commercialy available, OEM markets		3-electrode electrochemical cell, amperometric type, designed for Ethylene oxide	No Data	No Data	Maximum zero shift in pure air: < 2 ppm equivalent. Typical baseline range in pure air: 0 to 1 ppm equivalent	< 5 % / year	No data	Ethanol≈55%; Methyl-ethyl-ketone≈10%; Toluene≈20%; Carbon monoxide≈40%. Selectivity: bias voltage of +300mV. Recommended load resistor: 10 Ohms	2.25 ± 0.65 µA/ppm

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
RAE Systems Inc., 3775, North First Street, San Jose, CA 95134 USA, raesales@raesystems.com	Benzene: 50 ppb -200 ppm	60 s	Benzene: 50 ppb, resolution	No data	No data	Linearity ± 5% to 40 ppm benzene, Accuracy: ± 10 % display reading ± one digit benzene	No data	No data	No data	> 5 years	Benzene using a filter tube or Total aromatic compounds	No data	No data	No data
	IBE: 1 ppb -10 000 ppm using 10.6-eV lamp)	2 s	IBE: Resolution 1 ppb	No data	No data	10 to 2000 ppm: ±3% at calibration point	No data	No data	No data	> 5 years	VOC's with ionisation potentials < 10.6 eV	No data	No data	No data
City Technology Ltd, City Technology Centre, Walton Rd, Portsmouth PO6 1SZ, UK, Tel:+44 23 9232 5511, Fax:+44 23 9238 6611, www.citytech.com	0 - 20 ppm	< 140 s	100 ppb (resolution)	No data	1 % of signal	No data	No data	No data	< 5 % / year	2 years in air; 6 months stored in CLT container	(CO), hydrocarbons (HC), and VOCs (see data sheet)	No data	No data	No data
	0 - 20 ppm	< 120 s	100 ppb (resolution)	No data	2 % of signal	No data	No data	No data	< 5 % / year	2 years in air; 6 months stored in CLT container	(VOC)	No data	No data	No data
	0 - 20 ppm	< 140 s	100 ppb (resolution)	No data	1 % of signal	Linear	No data	No data	< 5 % / year	2 years in air; 6 months stored in CLT container	Ethanol≈55%; Methyl-ethyl-ketone≈10%; Toluene≈20%; Carbon monoxide≈40%. Selectivity: bias voltage of +300mV. Recommended load resistor: 10 Ohms	No data	No data	No data

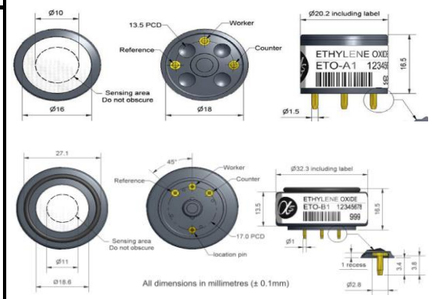
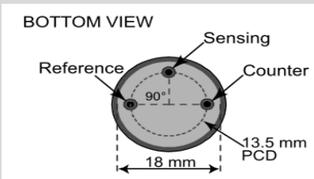
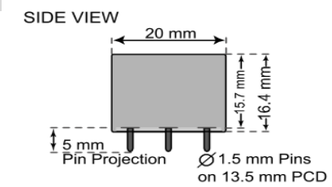
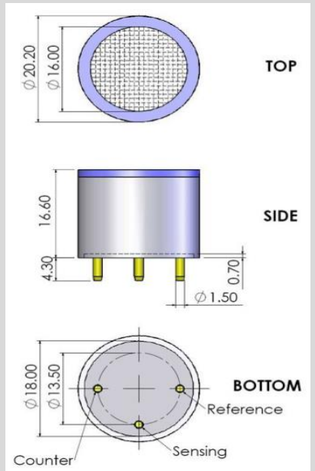
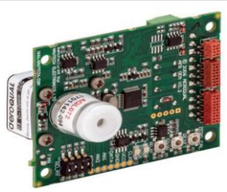
Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
RAE Systems Inc., 3775, North First Street, San Jose, CA 95134 USA, raesales@raesystems.com	Rechargeable, external field-replaceable lithium-ion battery pack (16 hours of operation), Alkaline battery adapter		No heater, UV lamp	Not relevant	Not relevant	Download data and upload instrument setup from PC through chargin cradle - Wireless data transmission through built-in BlueTooth	Operation from -20 to 50 °C, storage: -25 to 60 °C	Operation from 0 to 99 % (not condensing), Humidity compensation with built-in humidity sensor		738 g	Applications: Confined space entry, pre-screening during refinery and plant maintenance, Hazardous material response, Marine spill response, Refinery down-stream monitoring
	A 3.7V/ 3300mAH rechargeable Lithium-Ion battery pack (Battery Charging: Less than 8 hrs, Operation: > 12 hrs) or Alkaline battery holder (for 4 AA batteries)		No heater, UV lamp	Not relevant	Not relevant	260,000-point datalogging storage capacity for data download to PC . Bluetooth (2.4GHz), RF module (433MHz, 868MHz , 915MHz, or 2.4GHz)	Operation from -20 to 50 °C, tmeperature effect: no data	Operation from 0 to 95 % (not condensing), Humidity effect: no data		800 g	Applications: Confined space entry, pre-screening during refinery and plant maintenance, Hazardous material response, Marine spill response, Refinery down-stream monitoring
City Technology Ltd, City Technology Centre, Walton Rd, Portsmouth PO6 1SZ, UK, Tel:+44 23 9232 5511, Fax:+44 23 9238 6611, www.citytech.com	No data	No data	Not relevant	Not relevant	No data	Resistance	From -20 to 50 °C. Effectof temperature on sensor: no data	15 to 90% r.h., non-condensing. Effect of humidity on the sensor: no data	Atmospheric pressure ± 10 %. Effect of pressure: no data		No data
	No data	No data	Not relevant	Not relevant	No data	Resistance	From -20 to 50 °C. Effectof temperature on sensor: no data	15 to 90% r.h., non-condensing. Effect of humidity on the sensor: no data	Atmospheric pressure ± 10 %. Effect of pressure: no data		No data
	No data	No data	Not relevant	Not relevant	O	Resistance	From -20 to 50 °C. Effectof temperature on sensor: no data	15 to 90% r.h., non-condensing. Effect of humidity on the sensor: no data	Atmospheric pressure ± 10 %. Effect of pressure: no data		No data

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
RAE Systems Inc., 3775, North First Street, San Jose, CA 95134 USA, raesales@raesystems.com	No data	Not relevant, hand-held instrument	Data sheet and user manual	
	No data	Not relevant, hand-held instrument	Data sheet and user manual	
City Technology Ltd, City Technology Centre, Walton Rd, Portsmouth PO6 1SZ, UK, Tel:+44 23 9232 5511, Fax:+44 23 9238 6611, www.citytech.com	No data	No data	Data sheet	
	No data	No data	Data sheet	
	No data	No data	Data sheet	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
Alphasense Ltd, Sensor Technology House, 300 Avenue West, Skyline 120, Great Notley. CM77 7AA. UK. Telephone: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 E-mail: sensors@alphasense.com Website: www.alphasense.com	ETO-A1, similar features for ETO-B1, for ethylene oxide and other VOCs	Commercialy available, OEM markets		3 electrode electrochemical cell , amperometric type, designed for Ethylene oxide (ETO)	Linear model	Linear model, zero and span	No data	No data	No data	No correction given, the sensor seems sensitive to: ETO-A1: H2S, NO2, Cl2, NO, SO2, CO, H2, C2H4, NH3, HCHO, CO2. The ETO-B1 responds to most VOCs that are electrochemiclly active.	Ethylene oxide(ETO): 2.0 to 3.2 µA/ppm in 20ppm
MEMBRAPOR AG, Birkenweg 2, CH-8304 Wallisellen, Switzerland , Phone: +41 43 311 72 00 Fax : +41 43 311 72 01 Email: info@membrapor.ch www.membrapor.ch	ETO/M-10, for ethylene oxide and other VOCs	Commercialy available, OEM markets		3 electrode electrochemical cell , amperometric type, designed for Ethylene oxide (ETO)	Linear model: multi-point calibration expected	Linear model	Typical Baseline Range (pure air, 20°C) 0 to +1 ppm equivalent. No data about Zero drift	< 2 % signal loss/month	No data	No correction given, the sensor seems to be sensitive to CO, H2 and ethanol. It likely responds to most VOCs that are electrochemiclly active.	Ethylene oxide(ETO): 2.0 +- 0.5 µA/ppm
	ETO/C-20, for ethylene oxide and other VOCs	Commercialy available, OEM markets		3 electrode electrochemical cell , amperometric type, designed for Ethylene oxide (ETO)	Linear model: multi-point calibration expected	Linear model	Typical Baseline Range (pure air, 20°C) 0 to 1 ppm equivalent. No data about Zero drift	< 2 % signal loss/month	No data	No correction mentioned the sensor seems is reported to be sensitive to CO, H2 and ethanol. It likely responds to most VOCs that are electrochemiclly active.	Ethylene oxide(ETO): 2.5 +- 0.6 µA/ppm
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	EC4-10-ETO for ethylene oxide and other VOCs	Commercialy available, OEM markets		3 electrode electrochemical cell , amperometric type, designed for Ethylene oxide (ETO)	Linear model	Linear model across range	In zero air @ 20°C: -0.2 to 2.5 µA, baseline drift 0 to 2 ppm equivalent	< 2 % signal/month	No data	Correction given for: CO, EtOH, CH3OH, i-propanol, CH3COOH, i-butylene, butadiene, ethylene, propene, vinyl chloride, vinyl acetate, HCOOH, acrylonitrile with factor between 0.3 to 2.5	ETO: 1.9±0.8 µA/ppm
Aeroqual, Aeroqual Limited, 109 Valley Road, Mount Eden, Auckland, New Zealand, http://www.aeroqual.com/, Phone: +64 9 623 3013 Fax: +64 9 623 3012	VM	Commercialy available, OEM markets		Gas Sensitive Semiconductor (GSS), (Mixed metal oxide)	Linearised concentration output	multi-point calibration against isobutylene	No data	No data	None	None	calibration against isobutylene

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
Alphasense Ltd, Sensor Technology House, 300 Avenue West, Skyline 120, Great Notley. CM77 7AA. UK. Telephone: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 E-mail: sensors@alphasense.com Website: www.alphasense.com	0- 100 ppm	<150 s	100 ppb	No data	No data	5 to 10 ppm error at 40 ppm ETO (12.5 to 25 %)	No data	No data	No data	2 years	The bias voltage of +300mV is optimum for Ethylene Oxide but needs adjusting when measuring other VOCs.	No data	Temperature and humidity	Quantitative effect. See Operating conditions
MEMBRAPOR AG, Birkenweg 2, CH-8304 Wallisellen, Switzerland , Phone: +41 43 311 72 00 Fax : +41 43 311 72 01 Email: info@membrapor.ch www.membrapor.ch	0 – 10 ppm	< 140 s	Resolution 0.05 ppm	No data	< 2 % of signal	Linear, no details	No data	No data	< 2 % signal loss/month	Operation: 2 years in air. Storage Life: six months in container	Selectivity: the bias voltage of +300mV is optimum for Ethylene Oxide but needs adjusting when measuring other VOCs.	H2 @ 10 ppm: < 3 ppm , CO @ 10 ppm: < 5 ppm, Ethanol @ 10 ppm: < 6 ppm	No data	No data
	0 – 20 ppm - max 100 ppm	< 140 s	Resolution 0.1 ppm	No data	< 2 % of signal	Linear, no details	No data	No data	< 2 % signal loss/month	Operation: 2 years in air. Storage Life: six months in container, warranty: 1 year	Selectivity: the bias voltage of +300mV is optimum for Ethylene Oxide but needs adjusting when measuring other VOCs.	CO # 40 %, Toluene # 20 %, Ethanol 55 %	No data	No data
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	0-10 ppm	< 120 s	100 ppb (resolution)	No data	No data	Linear accross range	No data	Baseline drif: 0 to 2 ppm equivalen (ETO)	< 2 % signal/ month	Waranty 2 years, expected operating life 3 years, storage life 6 months in original packaging	Interference evaluated for a list of VOCs (see data sheet); the bias voltage of +300mV is optimum for ETO but needs adjusting when measuring other VOCs.	Quantitative effect, see data sheet	Temperature and humidity	Quantitative effect. See Operating conditions
Aeroqual, Aeroqual Limited, 109 Valley Road, Mount Eden, Auckland, New Zealand, http://www.aeroqual.com/, Phone: +64 9 623 3013 Fax: +64 9 623 3012	0-25 ppm	60s	Resolution 0.001 ppm	<0.05 ppm	No data	Linear response	No data	No data	No data	No data	Oxidising gases cause a negative response. Combustable gases cause a postive response.	semi-quantitative	No data	No data

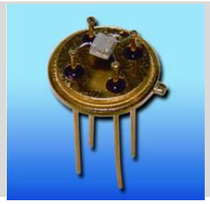
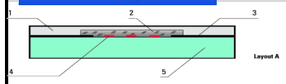
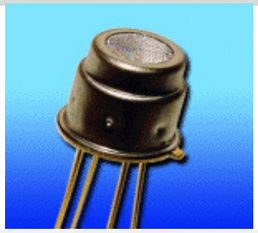
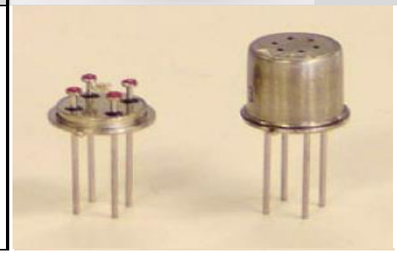
Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
Alphasense Ltd, Sensor Technology House, 300 Avenue West, Skyline 120, Great Notley. CM77 7AA. UK. Telephone: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 E-mail: sensors@alphasense.com Website: www.alphasense.com	No data	No data	Not relevant	Not relevant	No data	Current, used resistor to change to voltage	Operation: -0 to 50 °C. Effect: at zeoo ppm, output between 30 and 65 % of signal at 20 °C. At 50 °C, ouput between 110 and 140 % of response at 20 °C. Zero drift up to 4 ppm between -20 and 50 °C	From 15 to 90 %. Effect: No data	From 80 to 120 kPa		No data
MEMBRAPOR AG, Birkenweg 2, CH-8304 Wallisellen, Switzerland , Phone: +41 43 311 72 00 Fax : +41 43 311 72 01 Email: info@membrapor.ch www.membrapor.ch	No data	No data	Not relevant	Not relevant	No data	Current, used resistor to change to voltage	Opeartion: from - 20 °C to + 50 °C. Recommended Storage Temperature: 5 °C – 20 °C	From 15 % to 90 % R.H. non-condensing. Effect: No data	Atmospheric ± 10 %. Pressure Coefficient: No data	5.4 g	No data
	No data	No data	Not relevant	Not relevant	No data	Current, used resistor to change to voltage	Opeartion: from - 20 °C to + 50 °C. Recommended Storage Temperature: 5 °C – 20 °C	From 15 % to 90 % R.H. non-condensing. Effect: No data	Atmospheric ± 10 %. Pressure Coefficient: No data	13 g	No data
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	No data	No data	Not relevant	Not relevant	ECVQ-EK3	Current	Operation: -20°C to +50°C; Storage 0°C to 20°C; Effect at zero: from -20 to 20 °C, linear increase from -0.3 to 0 ppm; from 20 to 50 °C parbolic increase from 0 to 1.5 ppm. Effect at 100 ppm: from -20 to 50 °C nearly linear increase from 40 to 125 ppm.	From 15 - 90% RH (non-condensing). Effect: No data	From 90 to 110 kPa		Portable Gas Detectors
Aeroqual, Aeroqual Limited, 109 Valley Road, Mount Eden, Auckland, New Zealand, http://www.aeroqual.com/, Phone: +64 9 623 3013 Fax: +64 9 623 3012	11-15 VDC	<2W	No data	No Data	Aeroqual SM50	diagnostic LEDS, 0-5V signal, relay, RS232 and RS485 digital communications. I2C is available as an option	0 to 40°C	10 to 90%	No data		Outdoor environmental monitoring and indoor air quality

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
Alphasense Ltd, Sensor Technology House, 300 Avenue West, Skyline 120, Great Notley. CM77 7AA. UK. Telephone: +44 (0) 1376 556 700 Fax: +44 (0) 1376 335 899 E-mail: sensors@alphasense.com Website: www.alphasense.com	Effect of interfering gaseous compounds and temperature on datasheet	No data	Data sheet	
MEMBRAPOR AG, Birkenweg 2, CH-8304 Wallisellen, Switzerland , Phone: +41 43 311 72 00 Fax : +41 43 311 72 01 Email: info@membrapor.ch www.membrapor.ch	Effect of interfering gaseous compounds on datasheet	No data	Data sheet	
	Effect of interfering gaseous compounds on datasheet	No data	Data sheet	
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	Effect of interfering gaseous compounds and temperature on datasheet	No data	Data sheet	
Aeroqual, Aeroqual Limited, 109 Valley Road, Mount Eden, Auckland, New Zealand, http://www.aeroqual.com/, Phone: +64 9 623 3013 Fax: +64 9 623 3012	No data	No data	Info by mail of Geoff Henshaw (22 Oct. 2015)	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
UST Umweltsensortechnik GmbH, Dieselstraße 2 und 4, D-98716 Geschwenda, Tel: + 49 (0) 3 62 05 / 7 13-0, Fax: + 49 (0) 3 62 05 / 7 13-10, info@umweltsensortechnik.de	GGS 1330T	Commercialy available, OEM markets		SnO2 MOx sensor with wide range of application, especially suitable for leak detection of combustible gases	linear law with log scales Rs/R0 or better log(Rs/R0) = a+b log[]. The calibration is more linear for Rs/R=0= f(Log[])	No data, likely multi point calibration	No data	No data	No data	The Interfrence of CO and H2 is given in the datasheet and could be used for correction	CH4: -0.186 log(Rs/R0)/log([]ppm) or -0.240 (Rs/R0)/log([]ppm)
	GGS 2330T	Commercialy available, OEM markets		SnO2 MOx sensor for CO-, hydrogen- and alcohol, low cross sensitivity to CH4 methane.	linear law with log scales log(Rs/R0) = a+b log[]	No data, likely multi point calibration	No data	No data	No data	The Interfrence of CO is given in the datasheet and could be used for correction	C0: -0.361 (Rs/R0)/log([]ppm)
	GGS 3330T	Commercialy available, OEM markets		MOx for CH4, sensor for hydrocarbons, optimal for C1- C8 hydrocarbon	linear law with log scales Rs/R0 or better log(Rs/R0) = a+b log[]. The calibration is more linear for Rs/R0= f(Log[])	No data, likely multi point calibration	No data	No data	No data	The Interfrence of CO and H2 is given in the datasheet and could be used for correction	CH4:-0.227 log(Rs/R0)/log([]ppm) or -0.268 (Rs/R0)/log([]ppm)
	GGS 8330T	Commercialy available, OEM markets		MOx sensor for CH3CH2OH, low cross sensitivity to CH4 , CO and H2	linear law with log scales Rs/R0 or better log(Rs/R0) = a+b log[]	No data, likely multi point calibration	No data	No data	No data	The Interfrence of CO and H2 is given in the datasheet and could be used for correction	CH3CH2OH: -0.227 log(Rs/R0)/log([]ppm)
	TGS 2201: CO, CH3OH HC (e. g. i-butane)	Commercialy available, OEM markets		MOx sensor	linear law with log scales log(Rs/R0) = a+b log(C)	multi point calibration	No data	No data	No data	Use the calibration function of gaseous interfering compounds to correct (CO, CH3OH... (same model as for calibration of I-butane)	i-butane: -0.26 log(Rs/R0)/log(ppm)
	TGS 2600: CH4, CO, i-butane, ethanol, H2	Commercialy available, OEM markets		MOx sensor	linear law with log scales log(Rs/R0) = a+b log(C)	multi point calibration	No data	No data	No data	Correct with the calibration function of gaseous interfering compounds (CO, CH3OH, NO2, SO2 and H2S... (same model as for calibration of i-butane), correction for temperature and humidity (not linear)	i-butane: -0.24 log(Rs/R0)/log(ppm)

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
UST Umweltsensortechnik GmbH, Dieselstraße 2 und 4, D-98716 Geschwenda, Tel: + 49 (0) 3 62 05 / 7 13-0, Fax: + 49 (0) 3 62 05 / 7 13-10, info@umweltsensortechnik.de	CH4: 0 - 1000 ppm	No data	No data	No data	No data	No data	No data	No data	No data	No data	H2 and CO	Qunantitative for H2 and CO	No data	No data
	CO: 0 - 1000 ppm	No data	No data	No data	No data	No data	No data	No data	No data	No data	CH4 hydrogen and alcohol	Qunantitative for CH4	No data	No data
	CH4: 0 - 1000 ppm	No data	No data	No data	No data	No data	No data	No data	No data	No data	C1- C8 hydrocarbon, CO and H2	Qunantitative for CO and H2	No data	No data
	CH3CH2OH: 0 - 1000 ppm	No data	No data	No data	No data	No data	No data	No data	No data	No data	CH4, CO and H2	Qunantitative for CH4 and CO	No data	No data
	i-butane: 2-100 ppm	No data	iso butane: over 1 ppm	No data	No data	No data	No data	No data	No data	No data	CO, H2, CH3OH, other HC, with similar sensitivity, NO2, SO2 and H2S at a different load resistance	Quantitative effect	No data	No data
	i-butane, H2: 1 - 100 ppm	No data	i-butane: lower than 1 ppm	No data	No data	No data	No data	No data	No data	No data	Sorted by sensitivity: CH4, CO, i-butane, Ethanol, acetone, H2	Quantitative effect	Temperature and humidity	Quantitative effect

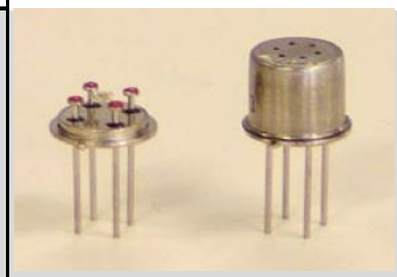
Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
UST Umweltsensortechnik GmbH, Dieselstraße 2 und 4, D-98716 Geschwenda, Tel: + 49 (0) 3 62 05 / 7 13-0, Fax: + 49 (0) 3 62 05 / 7 13-10, info@umweltsensortechnik.de	V = 5.0 V	No Data	P= 960 mW, sensor used at 450 °C	Constant. Temp. cycle Operation is possible (3S company)	No data	R= 50 ± 30 kOhms	No data	No data	No data	a few g	No data
	V = 4.5 V	No Data	P= 850 mW, sensor used at 450 °C	Constant. Temp. cycle Operation is possible (3S company)	No data	R= 200 ± 150 kOhms	No data	No data	No data	a few g	No data
	V = 4.5 V	No Data	P= 815 mW, sensor used at 420 °C	Constant. Temp. cycle Operation is possible (3S company)	No data	Direct Volatge (< 250 mV), R= = 50 ± 30 kOhms	No data	No data	No data	a few g	No data
	V = 5.1 V	No Data	P= 960 mW, sensor used at 460 °C	Constant. Temp. cycle Operation is possible (3S company)	No data	Direct Volatge (< 250 mV), R= = 30 ± 20 kOhms	No data	No data	No data	a few g	No data
	5.0 ± 0.2 V	15 mW	500mW	Constant	No data	No data (Rs betweeen 10 and 80 kOhms)	No data	No data	No data		responding to diesel and gasoline exhaust gases. This feature makes TGS2201 is an ideal senor for application in automatic damper control systems for automobile ventilation
	5.0 ± 0.2 V	15 mW	660 mW	Constant	No data	No data (Rs betweeen 1 and 10 kOhms)	-10 to 40 °C	RH: 35 to 100 %	No data		Air cleaners Ventilation control Air quality monitors

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
UST Umweltsensortechnik GmbH, Dieselstraße 2 und 4, D-98716 Geschwenda, Tel: + 49 (0) 3 62 05 / 7 13-0, Fax: + 49 (0) 3 62 05 / 7 13-10, info@umweltsensortechnik.de	No data	No data	Data sheet and Leidinger, M., Sauerwald, T., Reimringer, W., Ventura, G., Schütze, A., 2014. Selective detection of hazardous VOCs for indoor air quality applications using a virtual gas sensor array. Journal of Sensors and Sensor Systems 3, 253–263. doi:10.5194/jsss-3-253-2014	
	No data	No data		 Sensor structure: 1 sensitive layer, 2 insulating layer, 3 Pt-contacts, 4 Pt-heater, 5 ceramics substrate
	No data	No data		
	No data, calibration on datasheet only	No data	None	
	No data, calibration on datasheet only	No data	None	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
FIGARO USA, INC. , 121 S. Wilke Rd. Suite 300, Arlington Heights, Illinois 60005, Tel: (847)-832-1701, Fax: (847)-832-1705, figarousa@figarosensor.com	TGS 2602: H2, NH3, ethanol, H2S, toluene, CH4 in article	Commercialy available, OEM markets		MOx sensor	linear law with log scales log(Rs/R0) = a+b log(C)	multi point calibration	No data	No data	No data	Correct with the calibration function of gaseous interfering compounds (CO, CH3OH... (same model as for calibration of I-butane), correction for temperature and a slight correction for humidity	Toluene: -0.6 log(Rs/R0)/log(ppm)
	TGS 8100: Order of sensitivity CH4,i-butane, CO, H2 ethanol	Commercialy available, OEM markets		MOx sensor	linear law with log scales log(Rs/R0) = a+b log(C)	multi point calibration	No data	No data	No data	Correct with the calibration function of gaseous interfering compounds (CH4, CO... (same model as for calibration of i-butane), correction for temperature and humidity	i-butane: -0.14 log(Rs/R0)/log(ppm)
	TGS 822: CH4, CO, i-butane, n-hexane, benzene, ethanol	Commercialy available, OEM markets		MOx sensor	linear law with log scales log(Rs/R0) = a+b log(C)	multi point calibration	No data	No data	No data	Correct with the calibration function of gaseous interfering compounds (CO, CH3OH... (same model as for calibration of I-butane)	Benzene: -0.67 log(Rs/R0)/log(ppm)
	iAQ-100, broad range of reducing gases such as CO and VOCs	Commercialy available, OEM markets		MEMS metal oxide semi-conductor	No Data	No Data	No data	No data	Automatic baseline correction	No correction mentioned, the sensor seems is sensitive to: Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data. The sensor change of resistance is transformed into ppm VOC + CO2 equivalent units consisting of a list of VOCs (see Interference correction)
	iAQ-2000, broad range of reducing gases such as CO and VOCs	Commercialy available, OEM markets		MEMS metal oxide semi-conductor	No Data	No Data	No data	No data	Automatic baseline correction	No correction mentioned the sensor seems is sensitive to: Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data. The sensor change of resistance is transformed into ppm VOC + CO2 equivalent units consisting of a list of VOCs (see Interference correction)

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
FIGARO USA, INC. , 121 S. Wilke Rd. Suite 300, Arlington Heights, Illinois 60005, Tel: (847)-832-1701, Fax: (847)-832-1705, figarousa@figarosensor.com	toluene: 1-30 ppm	No data	toluene: lower than 1 ppm (likely around 0.1 ppm)	No data	No data	No data	No data	No data	No data	No data	Sorted by sensitivity: CH4, CO, i-butane, Ethanol, acetone, H2	Quantitative effect	Temperature and humidity	Quantitative effect
	i-butane: 1-30 ppm	No data	toluene: lower than 1 ppm (likely around 0.1 ppm)	No data	No data	No data	No data	No data	No data	No data	Sorted by sensitivity: CH4, CO, i-butane, Ethanol, acetone, H2	Quantitative effect	Temperature and humidity	Quantitative effect
	Benzene: 50-5000 ppm	No data	benzene: lower than 50 ppm	No data	No data	No data	No data	No data	No data	No data	Sorted by sensitivity: CH4, CO, i-butane, n-hexane, Ethanol, acetone	Quantitative effect	Temperature and humidity	Quantitative effect
	350-2000 ppm VOC + CO2 equivalents	15 min. Cold warm-up: 6 hours	350 ppm CO 2 equivalents	No data	No data	Linear between 350 and 2000 ppm: 10% pulse width → 350 ppm CO2 equivalents; 50% pulse width → 1175 ppm CO2 equivalents, 90% pulse width → 2000 ppm CO 2 equivalents	No data	No data	No data	No data	Sensitive to : Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data	No data	No data
	450-2000 ppm CO 2 equivalents	15 min	450 ppm CO 2 equivalents	No data	No data	No data	No data	No data	No data	No data	Sensitive to : Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data	No data	No data

Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
FIGARO USA, INC. , 121 S. Wilke Rd. Suite 300, Arlington Heights, Illinois 60005, Tel: (847)-832-1701, Fax: (847)-832-1705, figarousa@figarosensor.com	5.0 ± 0.2 V	15 mW	660 mW	Constant	No data	No data (Rs betweeen 1 and 10 kOhms)	10 to 50 °C tested	RH: 40 to 100 % tested	No data		Air cleaners, Ventilation control, Air quality monitors, VOC monitors and odor monitors
	5.0 ± 0.2 V	15 mW	660 mW	Constant	No data	No data (Rs betweeen 1 and 10 kOhms)	10 to 50 °C tested	RH: 40 to 100 % tested	No data		Air cleaners, Ventilation control, Air quality monitors, VOC monitors and odor monitors
	5.0 ± 0.2 V	15 mW	660 mW	Constant	No data	No data (Rs betweeen 1 and 10 kOhms)	-10 to 40 °C	RH: 35 to 100 %	No data		Breath alcohol detectors, Gas leak detectors/alarms, Solvent detectors for factories, dry, cleaners, and semiconductor
	12 VDC ± 2 VDC	550mW @ 12V	No data	No data	No data	Pulse Width modulation (PWM)	0 to +40°C (storage -40 to +85°C). No data available about the effect of temperature on the sensor	5 to 90% r.h., non-condensing.. No data available about the effect of humidity on the sensor.	No Data		Indoor Air Quality. When defined threshold limits are exceeded, the module alerts a climate control system to increase ventilation
	5.0 ± 0.25V, max. 20 mV ripple	30 mA	No data	No data	No data	TTL, RS232 (TTL level), I2C, 0-5V, PWM	0 to +50°C (storage: -25 to 75°C). No data available about the effect of temperature on the sensor	5 to 90% r.h., non-condensing.. No data available about the effect of humidity on the sensor.	No Data		Indoor Air Quality. When defined threshold limits are exceeded, the module alerts a climate control system to increase ventilation

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
FIGARO USA, INC. , 121 S. Wilke Rd. Suite 300, Arlington Heights, Illinois 60005, Tel: (847)-832-1701, Fax: (847)-832-1705, figarousa@figarosensor.com	No data, calibration on datasheet only	No data	None	
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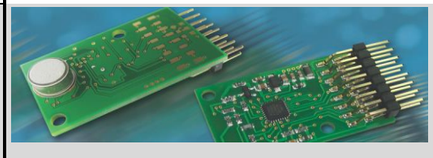
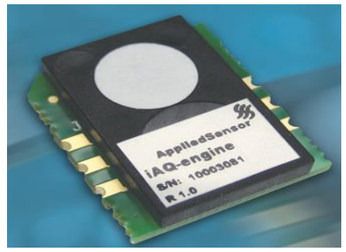
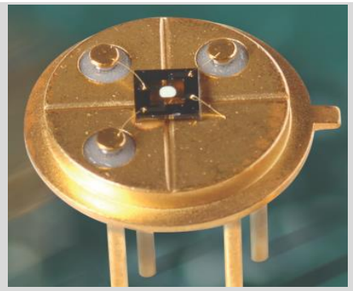
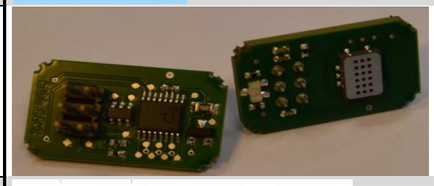
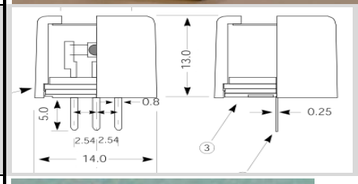
	No data, calibration on datasheet only	No data	None	
	No data	No data	Data sheet	
	No data	No data	Data sheet	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
AppliedSensor Sweden AB, Diskettgatan 11, SE-583 35 Linköping, Sweden, Tel: +46 13 262 900, Fax: +46 13 262 929	iAQ-engine, broad range of reducing gases such as CO and VOCs	Commercialy available, OEM markets		MEMS metal oxide semiconductor	No Data	No Data	No data	No data	Automatic baseline correction	No correction mentioned the sensor seems is sensitive to: Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data. The sensor change of resistance is transformed into ppm VOC + CO2 equivalent units consisting of a list of VOCs (see Interference correction)
	AS-MLV, highly sensitive to VOCs	Commercialy available, OEM markets		MEMS metal oxide semiconductor at 320 °C	No Data	No Data	No data	No data	No data. Zero air results in R in te 100-500k Ω range.	No correction mentioned the sensor seems is sensitive to: Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data. The sensor change of resistance is transformed into ppm VOC + CO2 equivalent units consisting of a list of VOCs (see Interference correction)
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	MICS-5121	Commercialy available, OEM markets		MEMS metal oxide semiconductor at 340 °Cfor reducing gases such as carbon monoxide, hydrocarbons and VOCs	No Data	Log (Rs/R0) = a + b log([CO])	No data	No data	No data	No data	CO: -0.59 log(Rs/R0)/log([] ppm). Sensitivity factor: Rs in air divided by Rs at 60 ppm of CO: 5 to 50
	MICS-5521 (likely identical to the performance of MICS-5121)	Commercialy available, OEM markets		MEMS metal oxide semiconductor at 340 °Cfor reducing gases such as carbon monoxide, hydrocarbons and VOCs	No Data	Log (Rs/R0) = a + b log([CO])	No data	No data	No data	No data	CO: -0.59 log(Rs/R0)/log([] ppm). Sensitivity factor: Rs at 60 ppm divided by Rs at 200 ppm: 3.0
	MICS-VZ-87	Commercialy available, OEM markets		MEMS metal oxide semiconductor at 340 °C to monitor VOCs and equivalent CO2	No Data	CO2 eq. = a + b Vout	No data	No data	No data	No data	CO: -0.59 log(Rs/R0)/log([] ppm). Sensitivity factor: Rs at 60 ppm divided by Rs at 200 ppm: 3.0
FIS Inc., 3-36-3, Kitazono, Itami, Hyogo, 664-0891 Japan, Tel: +81-72-780-1800, Fax: +81-72-785-0073, http://www.fisinc.co.jp	SP3_AQ2	Commercialy available, OEM markets		SnO2 semiconductor gas sensor to monitor various air pollution sources (e.g. VOCs) with quick response speed.	No data	linear or parabolic lines: log(Rs/R0) = f(log([]ppm)	No data	No data	No data	No data	CO: -0.4 log(Rs/R0)/log([] ppm). Sensitivity factor: Rs at 10 ppm H2 divided by Rs in air: 0.2 to 0.5
Synkera Technologies, Inc., 2605 Trade Centre Ave., Ste. C, Longmont, CO 80503 , USA, Tel: 1-720-494-8401, e-mail: info@synkera.com, www.synkera.com, fax: 720-494-8402 (fax)	VOC Sensor (P/n 731)	Commercialy available, OEM markets		SnO2 semiconductor gas sensor at 150 °C to monitor VOC.	No data		No data	No data	No data	The sensor is sensitive to many VOC (see data sheet).	ETOH: -1.166 log(Rs/R0)/log([] ppm).

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
AppliedSensor Sweden AB, Diskettgatan 11, SE-583 35 Linköping, Sweden, Tel: +46 13 262 900, Fax: +46 13 262 929	450-2000 ppm CO 2 equivalents	15 min.	450 ppm CO2 equivalents	No data	No data	No data	No data	No data	No data	No data	Sensitive to : Alcohols, Aldehydes, Aliphatic hydrocarbons, Amines, Aromatic hydrocarbons, CO, CH 4 , LPG, Ketones, Organic acids	No data	No data	No data
	450-2000 ppm CO 2 equivalents	seconds	No Data. Looking at response graph in data sheet, it is likely to be about 1 ppm	No data	No data	No data	No data	No data	No data	Years	Sensitive to : Alcohols, aldehydes, ketones, organic acids, amines, aliphatic and aromatic hydrocarbons. Limited cross-sensitivity to humidity, hydrogen and hydrocarbons	No data	No data	No data
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	CO: 1-1000 ppm	No data	No data	No data	No data	linear response of log of concentration vs log(Rs/R0)	No data	No data	No data	No data	detection of reducing gases such as carbon monoxide	No data	No data	No data
	CO: 1-1000 ppm	No data	No data	No data	No data	linear response of log of concentration vs log(Rs/R0)	No data	No data	No data	No data	detection of reducing gases such as carbon monoxide	No data	No data	No data
	CO2 equivalent: 400 - 1000 ppm	Similar to NDIR-CO2 sensors, new data every 1 s, warm-up 15 min	No data	No data	No data	Linear between 400 and 1000 ppm CO2 equivelent	No data	No data	No data	No data	detection of Wide VOCs detection range and CO2 equivalent	No data	No data	No data
FIS Inc., 3-36-3, Kitazono, Itami, Hyogo, 664-0891 Japan, Tel: +81-72-780-1800, Fax: +81-72-785-0073, http://www.fisinc.co.jp	EtOH: 0.1 to 100 ppm	Cold warm-up: 48 hrs	No data	No data	No data	May be linear or parabolic depending on gaseous compounds (see calibration model)	No data	No data	No data	No data	O2, other compound: no data	qualitative: O2 > 18 %	No data	No data
Synkera Technologies, Inc., 2605 Trade Centre Ave., Ste. C, Longmont, CO 80503 , USA, Tel: 1-720-494-8401, e-mail: info@synkera.com, www.synkera.com, fax: 720-494-8402 (fax)	No data in the 100 ppm range	<1 min (t90)	No data	No data	No data	No data	No data	No data	No data	No data	Isobutylene (200%), CO (30%), H2 (10%), CH4 (2%), NO2 Negative Resp. Formaldehyde (0%)	No data	No data	No data

Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
AppliedSensor Sweden AB, Diskettgatan 11, SE-583 35 Linköping, Sweden, Tel: +46 13 262 900, Fax: +46 13 262 929	5.0 ± 0.25V, max. 20 mV ripple	45 mA	No data	No data	No data	I2C, 0-5V	0 to +50°C (storage: -25 to 75°C). No data available about the effect of temperature on the sensor	5 to 90% r.h., non-condensing.. No data available about the effect of humidity on the sensor.	No Data		Indoor Air Quality. When defined threshold limits are exceeded, the module alerts a climate control system to increase ventilation
	5.0 ± 0.25V, max. 20 mV ripple	41 mW at 320°C	~2.7 V for 320°C, typical heater resistance 95Ω	No data	No data	Resistance	From -40° to 120°C (lower than op. temp.). No data available about the effect of temperature on the sensor	5 to 90% r.h., non-condensing. Light effect of humidity on the sensor.	No Data		Monitoring indoor air quality
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	5 ± 0.1 V	8 mW	2.4 V, 88 mW	constant	MK-EK1	Change of resistance, measurement of DC voltage	Operation: from -30 °C to 85 °C, storage: from -40 to 120 °C. Effect of temperature: no data	Operation and storage: from 5 to 90 %. Effect of humidity on sensor: no data	No Data		No data
	5 ± 0.1 V	8 mW	2.4 V, 88 mW	constant	MK-EK1	Change of resistance, measurement of DC voltage	Operation: from -30 °C to 85 °C, storage: from -40 to 120 °C. Effect of temperature: no data	Operation and storage: from 5 to 90 %. Effect of humidity on sensor: no data	No Data		No data
	5 ± 0.25 V	no data	250 mW	constant		Analog output and digital output (I2C)	Operation: from 0 °C to 50 °C, storage: from -40 to 80 °C. Effect of temperature: no data	Operation and storage: from 0 to 95 % (non condensing). Effect of humidity on sensor: no data	No Data		Monitor VOCs and CO2 equivalent variations in confined e.g. meeting rooms or vehicle cabins. The signal output can be used to control ventilation on-demand, saving energy and reducing cost-of-ownership.
FIS Inc., 3-36-3, Kitazono, Itami, Hyogo, 664-0891 Japan, Tel: +81-72-780-1800, Fax: +81-72-785-0073, http://www.fisinc.co.jp	5 V ± 4 % (AC or DC)	< 15 mW	315 mW, R = 57 Ohms ± 5%, 5.0 V ± 4 %	constant	No data	Analog output	Operation: from 0 °C to 40 °C, storage: from -10 to 70 °C. Effect of temperature: no data	Operation and storage: < 95 %; effect of humidity on sensor: no data	No Data		AIR QUALITY CONTROLS (VOCs)
Synkera Technologies, Inc., 2605 Trade Centre Ave., Ste. C, Longmont, CO 80503 , USA, Tel: 1-720-494-8401, e-mail: info@synkera.com, www.synkera.com, fax: 720-494-8402 (fax)	5.0 VDC	No data	400 mW, 3.5 V., R = 32 ± 2 Ohms	Constant	No data	Analog output	Operation: from -20 °C to 50 °C. Effect of temperature: no data	Operation and storage: 0 to 90 % (non condensing); effect of humidity on sensor: no data	No Data		No data

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
AppliedSensor Sweden AB, Diskettgatan 11, SE-583 35 Linköping, Sweden, Tel: +46 13 262 900, Fax: +46 13 262 929	No data	No data	Data sheet	
	No data	No data	Data sheet	
SGX Sensortech, 2 Hanbury Road, Chelmsford, Essex, CM1 3AE, United Kingdom, T: +44 (0)1245-809110, F: +44 (0)1245-809112, E: sales.is@sgxsensortech.com, www.sgxsensortech.com	No data	No data	Data sheet	
	No data	No data	Data sheet	
	No data	No data	Data sheet	
FIS Inc., 3-36-3, Kitazono, Itami, Hyogo, 664-0891 Japan, Tel: +81-72-780-1800, Fax: +81-72-785-0073, http://www.fisinc.co.jp	No data	No data	Data sheet	
Synkera Technologies, Inc., 2605 Trade Centre Ave., Ste. C, Longmont, CO 80503 , USA, Tel: 1-720-494-8401, e-mail: info@synkera.com, www.synkera.com, fax: 720-494-8402 (fax)	No data	No data	Data sheet	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
Unitec Srl - Via F.L. Ferrari, 31/D - 44122 Ferrara - Italy, Tel +39 0532 731123 - Fax +39 0532 730537	SENS 3000, SENS-IT	Commercialy available, OEM markets		Thick film sensor	Multi-point calibration	Exponential model given by manufacturer	< 2.5 % / 6 months ?	< 2.5 % / 6 months	No data	No data	No data
PID Analyzers, 2 Washington Circle, Unit 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=312	Model 312 Portable GC	Portable instrument, commercialy available		Portable GC with PID sensor) with on-column syringe injection or automatic with 6 port gas valve , oven. Target compounds: organics (VOCs by PID or FID) and inorganic species (H2S, NH3, AsH3…) that can be ionized by the PID lamp (9.5, 10.6 or 11.7 eV) . 50 liters at 1500 PSI; typical capillary column 15-20 cc/min; typical packed column 30-40 cc/min.	Manual. No data.	No data	Autozero on each run	<1% over 24 hours	NA- autozero on each run	No data, likely not needed as Gc is a selective method	No data
Electronic Sensor Technology 1125-B Business Center Circle Newbury Park, CA 91320 Telephone: 805-480-1994, www.estcal.com	zNose, model 4600	Portable instrument, commercialy available	Estcal	GC analyzer employing a trap, samples are seperated in heated column. Surface Acoustic Wave Quartz microbalance determining the mass of the component. Detects hydrocarbons in the range of C4 — C25. Carrier gas: He (min.99Q.999% Purity, #6), typical usage is 300 tests per day on one He charge or replaceable Cylinder) 95cc at 2560 psi. Typical usage: 200-300 tests	Automatic with user calibration	no data	No data	No data	no data	No data, likely not needed as Gc is a selective method	ppb-s
Defiant Technologies, 6814A Academy Parkway W NE, Albuquerque, NM 87109-4406, Telephone: (505) 999-5880, http://www.defiant-tech.com, info@defiant-tech.com	Frog 4000	Portable instrument, commercialy available	FKV srl, Largo delle Industrie 10, 24020 Torre Boldone (BG), Italy, tel: +39 035 3690211, Fax: +39 035 3690399, info@fkv.it	Hand-held, portable gas chromatography instrument with PID sensor and no carrier gas (ambient air)	Multi gas standards	As in Gc (multi-point, generally linear)	No data	No data	No data	No data, likely not needed as Gc is a selective method	No data
INFICON GmbH, Tel: +49.221.56788.100, Fax: +49.221.56788.9100, reach.germany@inficon.com	Explorer Portable Gas Chromatograph	Portable instrument, commercialy available		Portable gas chromatograph with 3 columns at 40-80 °C, PID sensor (10.6 eV) and internal cylinder for UHP N2/Zero Air as carrier gas	Multi gas standards	As for Gc (multi-point, generally linear)	No data	No data	No data	No data, likely not needed as Gc is a selective method	No data
	HapSite ER Chemical Identification System	Portable instrument, commercialy available		Person-portable Gas Chromatograph / Mass Spectrometer (GC/MS) for analysis of VOC in air	Multi gas standards	As in Gc (multi-point, generally linear)	No data	No data	No data	No data, likely not needed as Gc is a selective method	from ppt to low ppb with a concentrator for all detected compounds

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
Unitec Srl - Via F.L. Ferrari, 31/D - 44122 Ferrara - Italy, Tel +39 0532 731123 - Fax +39 0532 730537	0-30 ppb	< 3 s	lod and resolution: 0.1 µg/m³	No data	< 2 % f.s	Accuracy: ± 1 µg/m³	No data	< 2.5 % / 6 months ?	< 2.5 % / 6 months	No data	No data	No data	No data	No data
~~PID Analyzers, 2 Washington Circle, Unit~~ 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=312	PID - 10^8. The 312 has 3 ranges with computer controlled autoranging- x1, x 10, x 100.	Depends on retention times. 1st guess between 10 and 15 min	PID - 0.5 ppb benzene	No data	+/- 1-2% of reading	No data	No data	<1% over 24 hours	No data	No data	According to the selectivity of the used micro column	No data	No data	No data
Electronic Sensor Technology 1125-B Business Center Circle Newbury Park, CA 91320 Telephone: 805-480-1994, www.estcal.com	no data	5 to 60 sec	ppb-s	no data	std. dev < 2%	No data	No data	No data	No data	No data	Hydrocarbons in range of C4 to C25	No data	No data	No data
Defiant Technologies, 6814A Academy Parkway W NE, Albuquerque, NM 87109-4406, Telephone: (505) 999-5880, http://www.defiant-tech.com, info@defiant-tech.com	in the ppb range	5 min	in the ppb range	No data	No data	No data	No data	No data	No data	No data	According to the selectivity of the used micro column	No data	No data	No data
INFICON GmbH, Tel: +49.221.56788.100, Fax: +49.221.56788.9100, reach.germany@inficon.com	0.005 - 9999 ppm	No data	5 ppb	No data	No data	No data	No data	No data	No data	No data	According to the selectivity of the used columns. Generaly this is not a problem	Not relevant for GC?	Not relevant for GC?	Not relevant for GC?
	ppt to ppm depending on configuration	about 10 min	from ppt to low ppb with a concentrator for all detected compounds	No data	No data	No data	No data	No data	No data	Not relevant	According to the selectivity of the used columns. Generaly this is not a problem	Not relevant for GC?	Not relevant for GC?	Not relevant for GC?

Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
Unitec Srl - Via F.L. Ferrari, 31/D - 44122 Ferrara - Italy, Tel +39 0532 731123 - Fax +39 0532 730537	Vcc: +12 and -12 V	150 mW	No data	Constant	ETL3000	0-5 V	Operation: from -20 °C to 50 °C. Effect of temperature: no data	Operation: 0 to 95 % (non condensing); effect of humidity on sensor: no data	No Data		Ambient air monitoring
~~PID Analyzers, 2 Washington Circle, Unit~~ 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=312	115 VAC, 0.5 amps (12 VDC 5 amps). Battery: 3-4 hours; can operate off cigarette lighter adapter.	< 50 watts maximum	No heater, UV lamp	Not relevant	Embedded Pentium Computer with > 1 GByte of RAM; Windows XP® embedded stored on 2.5 GByte smart card	PeakWorks chromatography software and all data are on the memory stick.Data storage on 1 Gbyte USB memory stick. Analog output 0-1 VDC.	Operation: from 5 °C to 40 °C. Effect of temperature: no data	Operation and storage: 0 to 95 % (non condensing); effect of humidity on sensor: no data	No Data	15 x 30 x 23 cm. 5.4 kg	for environmental, quality control, natural gas... Applications
Electronic Sensor Technology 1125-B Business Center Circle Newbury Park, CA 91320 Telephone: 805-480-1994, www.estcal.com	Battery pack: 28VDC, 16AHr, Lithium-Ion, 4hr of use typical.	28*16/4 = 112 W	35 to 225 C	ramped from 0 - 18 C/s	Not relevant	USB port	0 to 40 °C	0 to 95 %, non-condensing	no data	Head: 2.6 kg, 31.8x10.9x17.3 cm. Support: 8.5 kg, 38.1x26.4x14.5xcm. Charger: 3.5 kg, 34.3x14x9.5 cm	Chemical, Environmental, Homeland Security, Life Science, Food & Beverage
Defiant Technologies, 6814A Academy Parkway W NE, Albuquerque, NM 87109-4406, Telephone: (505) 999-5880, http://www.defiant-tech.com, info@defiant-tech.com	Rechargeable NiMH Batt ery 9V, 5000 mAhr and AC power supply		No heater, UV lamp	Not relevant	Not relevant	Software for later peak integration, detection and quantification (USB)	No data	No data	No data		Defiant Technologies' FROG-4000 TM is a hand held micro system for detection of benzene, toluene, ethylbenzene, and xylenes (BTEX) and other VOCs (VOCs) in water, air, and soil. Environmental Monitoring of MTBE/BTEX
INFICON GmbH, Tel: +49.221.56788.100, Fax: +49.221.56788.9100, reach.germany@inficon.com	Rechargeable NiCd Battery , 8 hours autonomy		No heater, UV lamp	Not relevant	Not relevant	Display, Output to PC via PLC or SiteChart software	0 to 40 °C	0 to 95 % rel. Hum. Non condensing	No data		Ethylene monitoring for fruit and vegetable ripening, Process system monitoring, Environmental surveys, Spill characterization, Superfund cleanup, Underground storage tanks (UST), Soil gases/Soil Vapor Extraction (SVE) systems, EPA Compliance
	24 V, battery with 2-3 hours autonomy	30 W	Not relevant, N2 used as carried gas	Not relevant	Not relevant, data analysis using AMDIS Mass Spectral Libraries, NIOSH, (NIST on optional laptop)	Display with touch screen, WIFI, ethernet	5-45 °C	95 % non condensing	No data	19 kg	■ Environmental assessment ■ Chemical monitoring ■ Emergency response

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
Unitec Srl - Via F.L. Ferrari, 31/D - 44122 Ferrara - Italy, Tel +39 0532 731123 - Fax +39 0532 730537	No data	No data	Data sheet	
~~PID Analyzers, 2 Washington Circle, Unit~~ 4, Sandwich, MA 02563, USA, Phone: 1-774-413-5281, Fax: 1-774-413-5298, Sales Email: sales@hnu.com, http://www.hnu.com/products.php?v=312	No data	in a rugged plastic case	http://www.hnu.com/products.php?v=312	
Electronic Sensor Technology 1125-B Business Center Circle Newbury Park, CA 91320 Telephone: 805-480-1994, www.estcal.com	no data	not relevant	data sheet	
Defiant Technologies, 6814A Academy Parkway W NE, Albuquerque, NM 87109-4406, Telephone: (505) 999-5880, http://www.defiant-tech.com, info@defiant-tech.com	No data	Not relavant, hand-held instrument	User manual	
INFICON GmbH, Tel: +49.221.56788.100, Fax: +49.221.56788.9100, reach.germany@inficon.com	No data	Not relavant, Portable instrument	DataSheet, User manual	
	The manufacturer mention about the U.S. EPA and U.S. Air Force (USAF) partnering on an evaluation of the Inficon HAPSITE but we cannot find evaluation	Not relavant, Portable instrument	DataSheet, User manual	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						Sensitivity
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	
	HapSite smart/smart plus	Portable instrument, commercialy available		Person-portable gas chromatograph/mass spectrometer (GC/MS) for VOCs and select SVOCs	Multi gas standards	As in Gc (multi-point, generally linear)	No data	No data	No data	No data, likely not needed as Gc is a selective method	from high ppt to low ppb with a concentrator for all detected compounds
FemtoScan	Environmental Vapor Monitor (EVM) II	Portable instrument, commercialy available	http://www.femtoscan.com/femtosca.htm	Automated Vapor Sampling-Transfer Line Gas Chromatography. GC/IMS , Ion Mobility Spectrometry (IMS)	No data	No data	No data	No data	No data	No data, likely not needed as both the GC and IMS are selective method	No data
Bentekk	Gas Chromatography in your hand	Commercial hand-held instrument, in final development step	http://www.bentekk.com/wp-content/uploads/2015/04/bentekk_broshure_04_2015.pdf	Portable gas chromatograph coupled with photo ionization detection .	No data	No data	No data	No data	No data	No data, likely not needed as Gc is a selective method, the instrument can identify more than 40 compounds	50 ppb in data sheet, 25 ppb in a personal communication, aim to reduce to 1.5 ppb (maybe by the end of 2015)
The eNose Company, 'Hof van Zutphen', Industrieweg 85, 7202 CA Zutphen, The Netherlands, Tel. +31 885 585 266, Fax +31 885 585 26, 7E-mail info@eNose.nl, www.enose.nl	Aerekaprobe	Portable instrument, commercialy available	The eNose Company	System with 1 to 12 non-specific sensors and pattern recognition software. Micro-hotplate metal-oxide sensors, temperature modulated.	Multiple samples	No data, calibration with multiple reference samples	No data	No data	No data	Pattern recognition software	No data
Comon-Invent, Burgemeestersrand 198a 2625 NZ Delft The Netherlands, +31 15-2855399 info@comon-invent.com, www.comon-invent.com	eNose	Portable instrument, commercialy available	Comon-Invent	Sensor array with 4 semi-conductor sensors, pattern recognition software	No data	No data	No data	No data	No data	No data	No data
Owlstone Ltd, 127 Cambridge Science Park, Milton Road, CambridgeCB4 0GD, Tel: +44 (0)1223 428200, Fax: +44 (0)1223 428201, www.owlstonenanotech.com	Lonestar	Portable instrument, commercialy available	Owlstone	portable gas monitor based on Assymetric Ion Mobility Spectrometry (FAIMS)	no data	no data	No data	No data	no data	No data	no data

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
	high ppt to ppm depending on configuration	about 15 min	from high ppt to low ppb with a concentrator for all detected compounds	No data	No data	No data	No data	No data	No data	Not relevant	According to the selectivity of the used columns. Generaly this is not a problem	Not relevant for GC?	Not relevant for GC?	Not relevant for GC?
FemtoScan	No data	real time in seconds	benzene: 539 ppb	No data	No data	No data	No data	no data	No data	Not relevant	Separation by GC for Alkanes, Cyclo-Alkanes, Alkenes, Alcohols, Aromatics, Ketones, Esters, Organo Phosphonates, Pesticides, Amines, Pyridines, Phenols, Organic Acids, Aldehydes, Halides,	Quantitative, see data sheet	No data	No data
Bentekk	No data	30 s	50 ppb in data sheet, 25 ppb in a personal communication, aim to reduce to 1.5 ppb (maybe by the end of 2015)	No data	No data	No data	No data	no data	No data	Not relevant	Separation by GC for more than 40 compounds	Likely quantitative	No data	No data
The eNose Company, 'Hof van Zutphen', Industrieweg 85, 7202 CA Zutphen, The Netherlands, Tel. +31 885 585 266, Fax +31 885 585 26, 7E-mail info@eNose.nl, www.enose.nl	Above 1 ppm	20 seconds	1 ppm	No data	No data	No data	No data	No data	No data	No data	volatile hydrocabons and inorganic substances that react with oxygen at the sensor surface	No data	No data	No data
Comon-Invent, Burgemeestersrand 198a 2625 NZ Delft The Netherlands, +31 15-2855399 info@comon-invent.com, www.comon-invent.com	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
Owlstone Ltd, 127 Cambridge Science Park, Milton Road, CambridgeCB4 0GD, Tel: +44 (0)1223 428200, Fax: +44 (0)1223 428201, www.owlstonenanotech.com	no data	no data	1 ppb	no data	no data	no data	no data	no data	no data	no data	BTEX, VOCs	quantitative	no data	no data

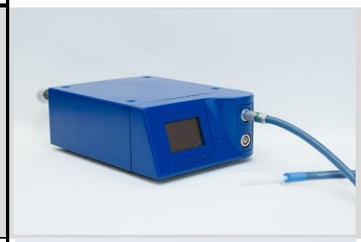
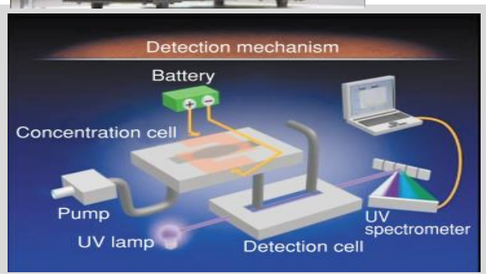
Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
	24 V, battery with 2-3 hours autonomy	30 W	Not relevant, N2 used as carried gas	Not relevant	Not relevant, data analysis using AMDIS Mass Spectral Libraries, NIOSH, (NIST on optional laptop)	Display with touch screen, WIFI, ethernet	5-45 °C	95 % non condensing	No data	19 kg	detect, identify and quantify toxic industrial chemicals (TICs) and chemical warfare agents (CWAs) on-site
FemtoScan	regulated 24 VDC	2.0 A (thus 48 W)	no data	no data	not applicable	DC 4-20 mA, 2 alarm relays, 1 fault relay	0 to 30 C	sensor dependent, typically 20 to 95 %	no data		Continuous gas detection system to measure and detect hazardous gas leaks in the workplace
Bentekk	Battery mode for 6 hours, 220 V?	No data	no data	no data	not applicable	Wireless data to tablet	Nodata	No data	no data	1 kg	Clearance measurements for safety, Threshold limit values (TLV), Preserving and monitoring of our environment, Immediate danger identification, Analysis on your workbench
The eNose Company, 'Hof van Zutphen', Industrieweg 85, 7202 CA Zutphen, The Netherlands, Tel. +31 885 585 266, Fax +31 885 585 26, 7E-mail info@eNose.nl, www.enose.nl	5V, 1A (max). Battery pack Li-ion LIP18650, 3.7V	3 hours on battery	Heater	Thermo-cycling from 180 to 340 C	Not relevant	Daemeter software for data evaluation	5 to 40 C +- 0.2 C	Max 90% +- 3%	No data		Laboratory and field use.
Comon-Invent, Burgemeestersrand 198a 2625 NZ Delft The Netherlands, +31 15-2855399 info@comon-invent.com, www.comon-invent.com	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
Owlstone Ltd, 127 Cambridge Science Park, Milton Road, CambridgeCB4 0GD, Tel: +44 (0)1223 428200, Fax: +44 (0)1223 428201, www.owlstonenanotech.com	120/240 VAC	110 W	heater up to 70 C	no data	Not relevant	USB, RJ45, GPIO, Bluetooth, offline analysis software	5 to 40 C	5 to 90 %	no data		monitoring of: laboratory, reaction, fermentation, bioreactor off-gas, pharmaceutical solvent drying, food and beverage taints, food freshness and odours, gas purity, gas scrubber efficiency and breakthrough, leaks and ingress, recirculated atmospheres, glovebox monitoring, material verification, cleaning verification

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
	The manufacturer mention about the U.S. EPA and U.S. Air Force (USAF) partnering on an evaluation of the Inficon HAPSITE but we cannot find evaluation	Not relavant, Portable instrument	DataSheet, User manual	
	no data	not applicable	user manual	
FemtoScan				
Bentekk	no data	not applicable	user manual	
The eNose Company, 'Hof van Zutphen', Industrieweg 85, 7202 CA Zutphen, The Netherlands, Tel. +31 885 585 266, Fax +31 885 585 26, 7E-mail info@eNose.nl, www.enose.nl	No data	Not relevant.	User manual	
Comon-Invent, Burgemeestersrand 198a 2625 NZ Delft The Netherlands, +31 15-2855399 info@comon-invent.com, www.comon-invent.com	No data	No data	No data	
Owlstone Ltd, 127 Cambridge Science Park, Milton Road, CambridgeCB4 0GD, Tel: +44 (0)1223 428200, Fax: +44 (0)1223 428201, www.owlstonenanotech.com	No data	not relevant	Data sheet	

Manufacturer	Model	Availability	Supplier (if different form manufacturer)	Principle of operation	Data treatment						
					Calibration method	calibration formula	zero drift	Span drift	zero correction	interference correction	Sensitivity
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	PEN3 - Portable Electronic Nose	Portable instrument, commercialy available	Airsense	10 different metal oxides single thick film sensors, optional adapted to application. Hot sensors working temperature 350 to 500 C. Pattern recognition analysis software. Target: odours	no data	no data	no data	no data	no data	no data	no data
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	Gas Detector Array - Fumigation	Portable instrument, commercialy available	Airsense	Hybrid Sensor Array comprising different detection technologies	no data	no data	no data	no data	no data	no data	no data
Pure Aire monitoring systems, inc, 557 Capital Drive, Lake Zurich IL 60047-6711 Toll Free: 888.788.8050 • Phone: 847.726.6000 Fax: 847.726.6051 • Email:info@pureaire.net, www.pureairemonitoring.com	Air check Advantage Benzene Gas Monitor	Portable instrument, commercialy available	PureAire	Smart renewable electrochemical cell linked to a compact pyrolizer. Sample is drawn through the pyrolizer where Benzene is thermally decomposed and converted into another gas that is more easily detected electrochemiclly	no data	no data	No data	No data	no data	no data	no data
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	Horiuchi, T. et al., 2006. Portable Aromatic VOC Gas Sensor for Onsite Continuous Air Monitoring with 10-ppb Benzene Detection Capability. *NTT Technical Review* , 1, pp.30–37.	Portable instrument, possibly commercialy available more likely a prototype	?	Ultraviolet (UV) absorption spectroscopy with microfluidic device for BTEX	By proportionality to reference spectra	Linear equation	No data	No drift over 30 days at 10 ppb	Not needed	By wavelength selection and correction. Decomposed (deconvolution?)	Not relevant
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	S. Camou, T. Horiuchi, and T. Haga, “Ppb Level Benzene Gas Detection by Portable BTX Sensor Based on Integrated Hollow Fiber Detection Cell,” Proc. of IEEE Sensors 2006, Daegu, Korea, 2006	Portable instrument, possibly commercialy available more likely a prototype	?	Ultraviolet (UV) absorption spectroscopy with microfluidic device for BTEX, Pulse pump system and new detection cell added.	By proportionality to reference spectra	Linear equation	No data	No drift over 30 days at 10 ppb	Not needed	By wavelength selection and correction. Decomposed (deconvolution?)	Not relevant

Manufacturer	Sensitivity							Stability			Selectivity			
	range of concentration	response time	limit of detection	limit of quantification	Repeatability	linearity	hysteresis	short term drift	long term drift	lifetime	Chemical compounds	qualitative or quantitative effect	physical interference	qualitative or quantitative effect
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	ppb to upper ppm	15 sec	ppb	No data	No data	No data	No data	No data	No data	Battery operating time 4hrs	Benzene, Phosphine, Formaldehyde, Carbon Disulfide, Ethylene Oxide, Ammonia, and more	No data	No data	No data
Pure Aire monitoring systems, inc, 557 Capital Drive, Lake Zurich IL 60047-6711 Toll Free: 888.788.8050 • Phone: 847.726.6000 Fax: 847.726.6051 • Email:info@pureaire.net, www.pureairemonitoring.com	0 to 20 ppm	T90 < 40 to 60 s	ppm level	No data	10%	no data	No data	no data	No data	1 to 3 years under normal operation	Benzene and others	Quantitative, see data sheet	No data	No data
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	10-100 ppb	1 hour, 50 min for preconcetration at 25 ppb	10 ppb, it would depend on preconcentration time, S/N of 3	Likely 3.3 times the limit of detection	No data	Good linearity in a low concentration range 10–100 ppb)	No data	No data	See span drift over 30 days. Mean 0.124 10^{-2} ± 0.989 10^{-4} absorbance unit	No data	By wavelength selection and correction. Decomposed (deconvolution?)	No data	No data	No data
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	0-10 ppb	1 hour, 50 min for preconcetration at 25 ppb	1 ppb, it would depend on pre-concentration time, S/N of 3	Likely 3.3 times the limit of detection	No data	Good linearity in a low concentration range 10–100 ppb)	No data	No data	See span drift over 30 days. Mean 0.124 10^{-2} ± 0.989 10^{-4} absorbance unit	No data	By wavelength selection and correction. Decomposed (deconvolution?)	No data	No data	No data

Manufacturer	Power suplpy	Power consumption	Heater/Lamp		Test board	Output	Operating conditions			weight	Suggested application
			power consumption	working pattern			temperature	relative humidity	pressure		
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	110 to 230 VAC or 12VDC	30 W	no data	no data	no data	USB or RS-232, data logger, off-line analysis software	0 to 45 C	5 to 95 %	no data		process, quality and safety control, environment
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	No data	no data	no data	no data	Not relevant	display reading	0 to 45 C	no data	no data		sreening containers for hazardous gases before being entered
Pure Aire monitoring systems, inc, 557 Capital Drive, Lake Zurich IL 60047-6711 Toll Free: 888.788.8050 • Phone: 847.726.6000 Fax: 847.726.6051 • Email:info@pureaire.net, www.pureairemonitoring.com	regulated 24 VDC	2.0 A (thus 48 W)	no data	no data	not applicable	DC 4-20 mA, 2 alarm relays, 1 fault relay	0 to 30 C	sensor dependent, typically 20 to 95 %	no data		Continuous gas detection system to measure and detect hazardous gas leaks in the workplace
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	100 V	No data	Not relevant	Not relevant	Laptop	laptop	No data	No data	No data	a few kg, 33 cm wide, 15.5 cm deep, and 17 cm high	Continuous ambient and indoor ai quality monitoring
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	100 V	No data	Not relevant	Not relevant	Laptop	laptop	No data	No data	No data	a few kg, 33 cm wide, 15.5 cm deep, and 17 cm high	Continuous ambient and indoor ai quality monitoring

Manufacturer	Availability of sensor evaluation	Box/ sensor holder details	References	
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	no data	no data	data sheet	
AIRSENSE Analytics GmbH Hagenower Straße 73 19061 Schwerin / Germany T +49 385 3993-280 F +49 385 3993-281 info@airsense.com	no data	not relevant	data sheet	
Pure Aire monitoring systems, inc, 557 Capital Drive, Lake Zurich IL 60047-6711 Toll Free: 888.788.8050 • Phone: 847.726.6000 Fax: 847.726.6051 • Email:info@pureaire.net, www.pureairemonitoring.com	no data	not applicable	user manual	
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	No data	Not Applicable	Horiuchi, T. et al., 2006. Portable Aromatic VOC Gas Sensor for Onsite Continuous Air Monitoring with 10-ppb Benzene Detection Capability. *NTT Technical Review* , 1, pp.30–37.	
NTT Microsystem Integration Laboratories, Atsugi-shi, 243-0198 Japan, E-mail: thoriuch@aecl.ntt.co.jp	No data	Not Applicable	Horiuchi, T. et al., 2006. Portable Aromatic VOC Gas Sensor for Onsite Continuous Air Monitoring with 10-ppb Benzene Detection Capability. *NTT Technical Review* , 1, pp.30–37.	

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